Neutron Imaging of Advanced Transportation Technologies

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Annual Merit Review

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ORNL is managed by UT-Battelle for the US Department of Energy

DOE VTO Management Team
Gurpreet Singh, Leo Breton & Ken Howden

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Project Overview

Timeline

- Year 1 of 3-year program
  - 2016 Lab Call Task 7*

*- Part of large ORNL project "Multi-cylinder Advanced Combustion Engine Development and Controls"

Budget

- FY2017: $185k
- FY2016: $200k

Partners

- BES-funded neutron scientists and facility operation
- Academia
  - University of Tennessee, Boston University and MIT
- Industry
  - GM, Continental Automotive, MIT consortium members (12+)

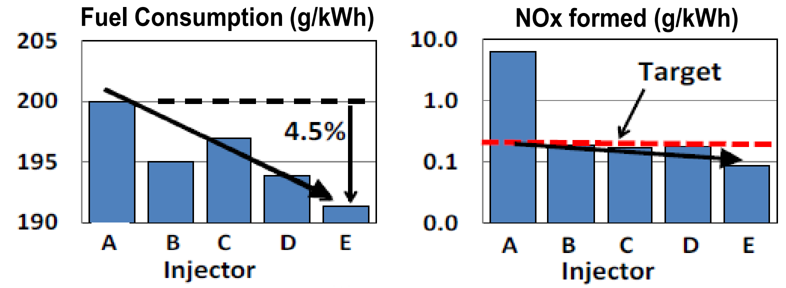
Barriers

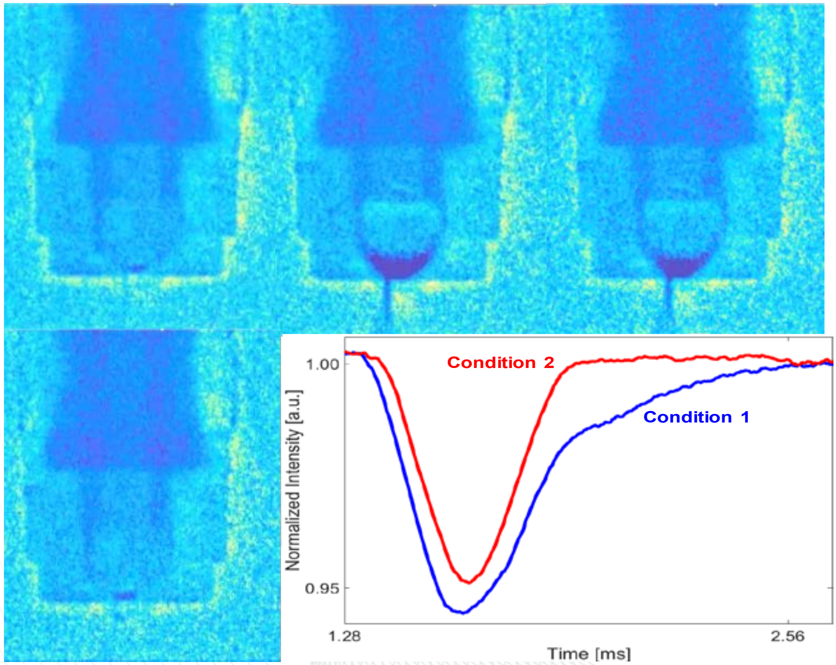
- **2.3.1B: Lack of cost-effective emission control**
  - Improved regeneration efficiency in particulate filters (PFs)
- **2.3.1C: Lack of modeling capability for combustion and emission control**
  - Improved models of fluid flow inside fuel injectors
  - Need to improve models for effective PF regeneration with minimal fuel penalty
- **2.3.1.D: Durability**
  - Fuel injector durability
  - Potential for PF thermal runaway
  - Ash deposition and location in PFs which limit durability

Objectives and Relevance

Implement non-destructive, non-invasive neutron imaging technique to improve understanding of advanced vehicle technologies

- Injectors: gasoline direct injection (GDI)
  - Goal: Visualize internal flow dynamics
    - Fluid density variation including location and timing of cavitation
  - Aid model development; injector design
    - **Injector design significantly influences efficiency and emissions***
  - Diesel and urea also possible
- Particulate filters (PF)
  - Effort primarily moved to other projects, but technique developed here
  - Both gasoline and diesel PFs
  - Comprehensive, quantitative device analysis targeting model parameters





* - e.g., Keith Confer (Delphi), "Gasoline Ultra Fuel Efficient Vehicle", 2012 DOE AMR, Crystal City, VA, ACE064, May 18, 2012.

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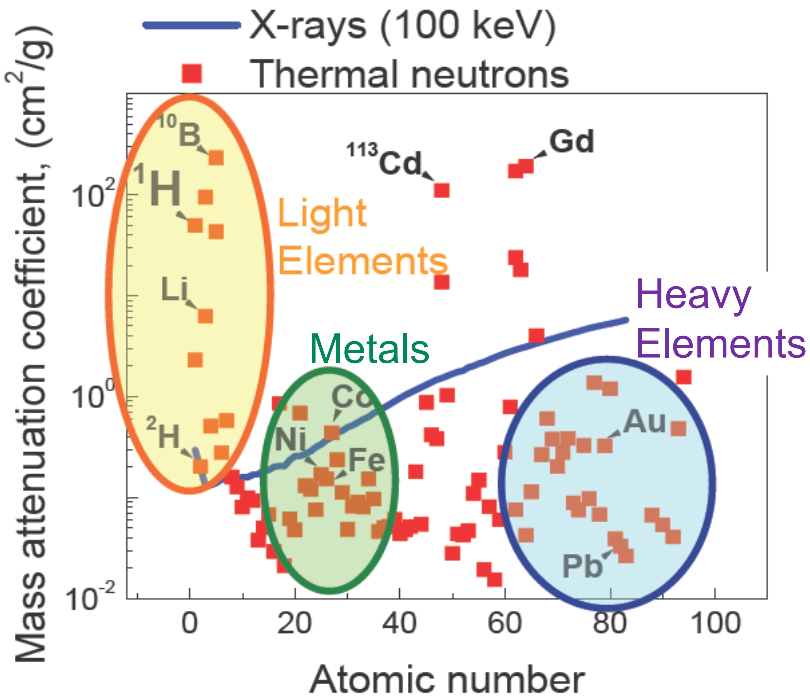
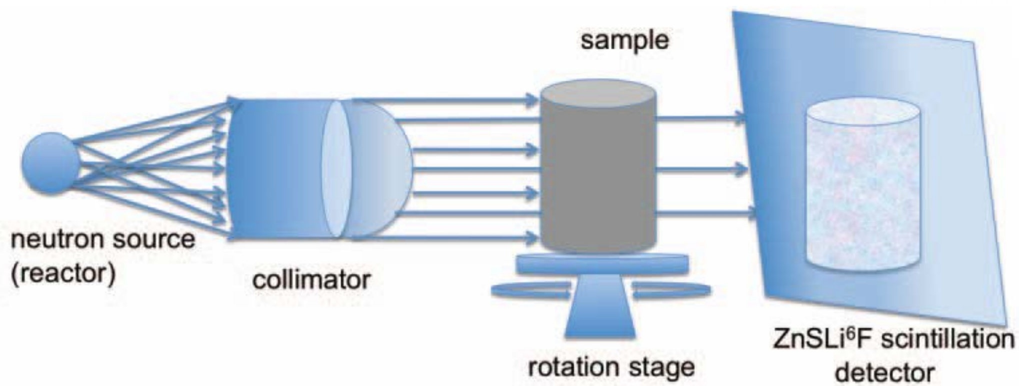
Neutrons can penetrate metals while still strongly interacting with light elements

- Neutrons are heavily attenuated by some light elements (^{1}H, ^{10}B, etc)
  - Can penetrate metals with minimal interactions
  - Highly sensitive to water and hydrocarbons/fuel
  - Image is based on absence of neutrons
- X-ray absorption increases for heavy/dense elements





Neutron imaging is a complementary analytical tool

Attenuation Coefficient Reference: N. Kardjilov's presentation at IAN2006
http://neutrons.ornl.gov/workshops/ian2006/MO1/IAN2006oct_Kardjilov_02.pdf

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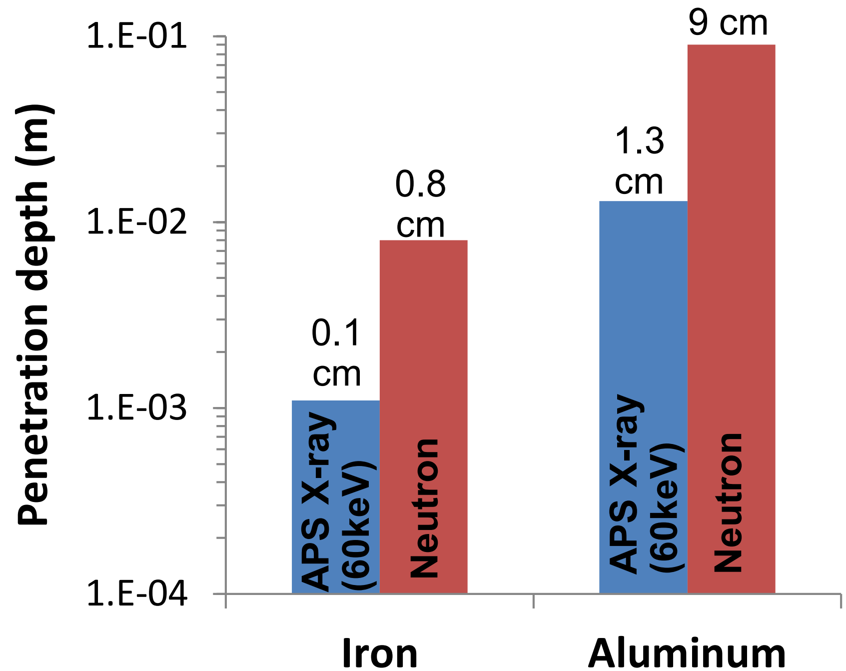

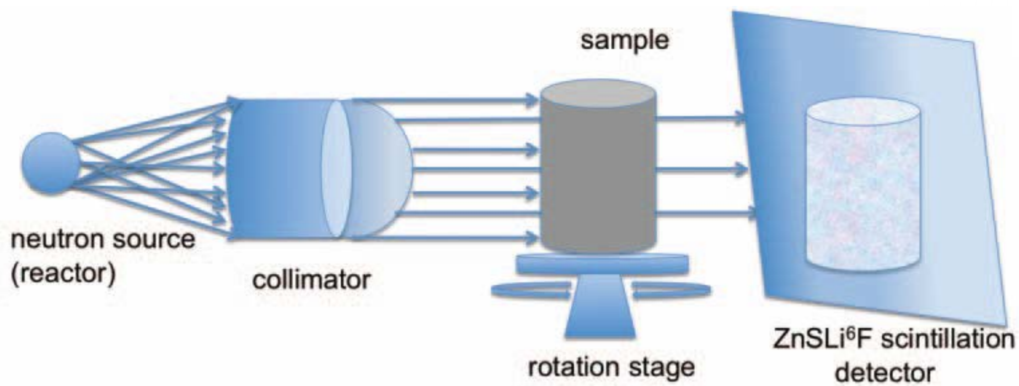

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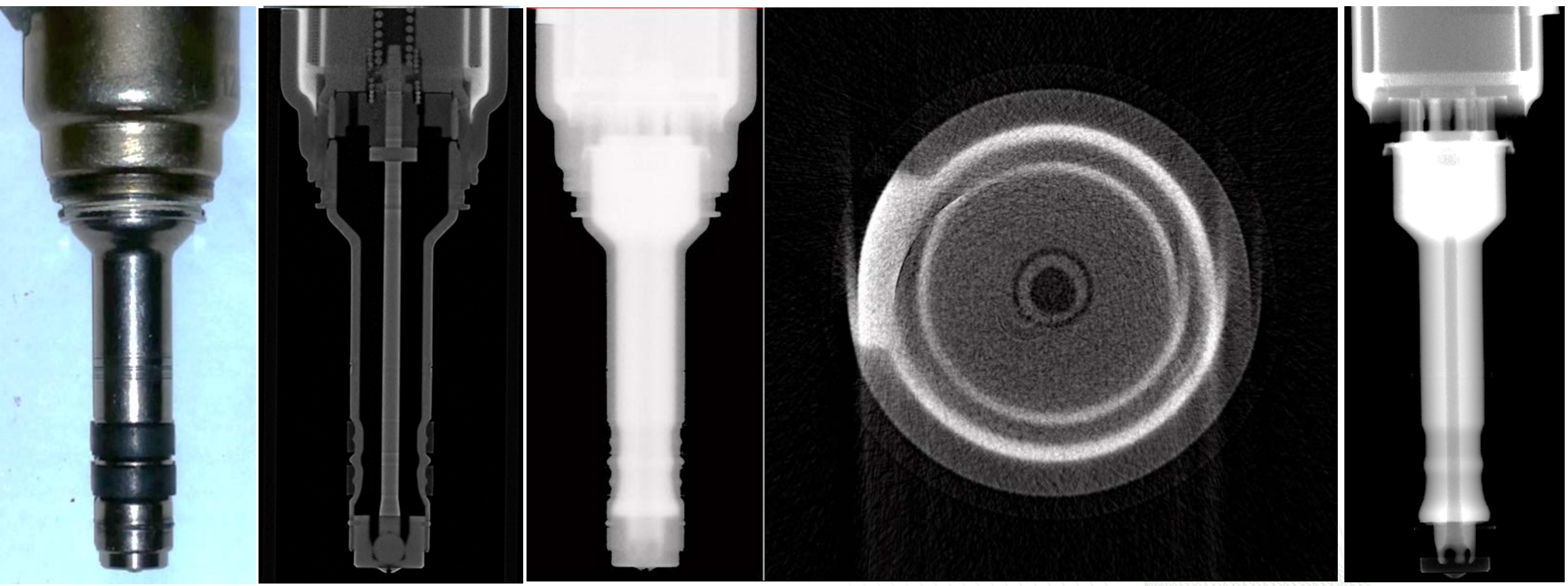
Neutron Penetration depth : R. Pynn, "Neutron scattering: a primer." *Los Alamos Science* 19 (1990): 1-31. APS X-ray penetration depth: C. Powell, personal communication.

Complete sample analysis can be achieved with non-destructive techniques

- Samples can be analyzed at one cross-section or a complete reconstruction can provide a cross-section of the entire sample
  - Originally ~50 microns achievable at ORNL's High Flux Isotope reactor (HFIR)
  - As low as 10-20 microns possible with MCP (Micro-Channel Plate) detector
- Illustration of technique on GDI-based injector with fuel inside:



Empty Fuel-filled H-containing

Milestones

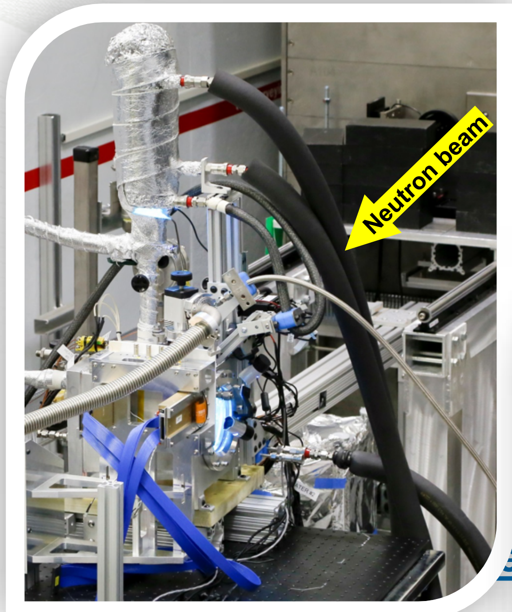
- {SMART} Demonstrate chamber and dynamic neutron detection can occur using ECN-relevant fuel (iso-octane) and temperatures (9/30/2016).
  - **Completed**
- Complete a high resolution computerized tomography scan of the ECN spray G injector body and share results with the ECN community (9/30/2017).
  - **Completed**
- {SMART} Provide relevant fluid dynamics data from neutron imaging to the ECN research community for three conditions using iso-octane (9/30/2019).
  - ON TRACK

Collaborations

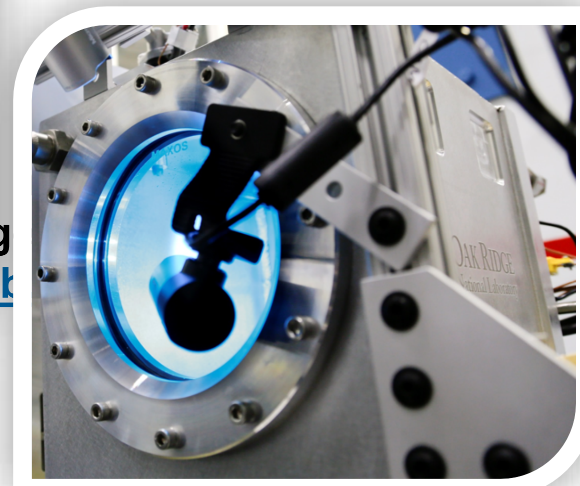
- **Basic Energy Sciences** (Hassina and Jean-Christophe Bilheux)
  - High Flux Isotope Reactor (HFIR); Spallation Neutron Source (SNS)
  - Development and operation of beamline facilities
  - Scientists' time, data reconstruction, analysis and writing publications
- **University of Tennessee** (Jens Gregor, Alex Pawlowski)
  - JG: Developing algorithms for improving contrast, 3-D tomography and removing artifacts
  - AP: Bredesen Center Fellow, CAD development, image analysis
- **GM** (Ron Grover, Scott Parrish)
  - Coordination of injectors
- **Continental Automotive** (Bill Imoehl, Nic Van Vuuren)
  - Fouled and clean injectors, urea injectors
- **MIT Consortium** (J. Kamp, A. Sappok, V. Wong, 12+ members)
  - Ash filled DPFs, X-ray CT-scans and detailed analytical discussions
- **University of California** (Anton Tremsin)
  - Development and installation of MCP detector at ORNL
- **Boston University** (Emily Ryan, Sheryl Grace, Glynn Holt)
  - Development and multiscale validation of Euler-Lagrange based computational methods for modeling fluid dynamics in fuel injectors

Approach

Receive or obtain relevant devices

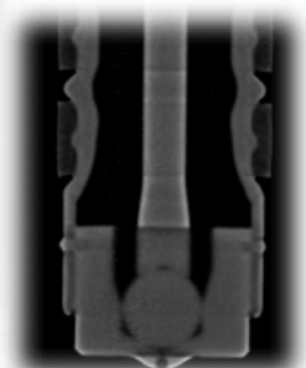


Record raw images of devices with neutron beam, scintillator and/or MCP detector

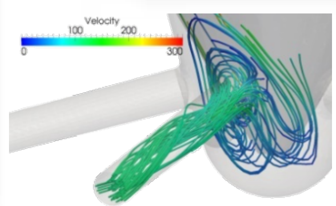


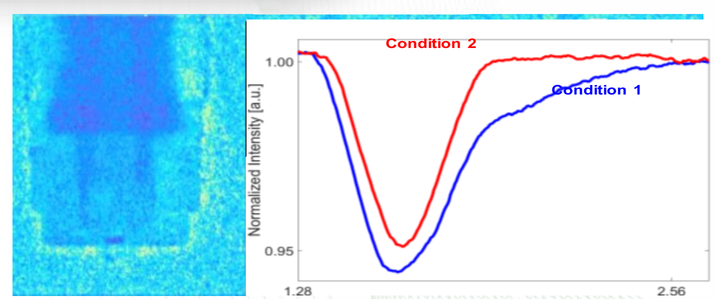
Non-destructive technique allows multiple studies to be performed on single commercial or prototype device

Reconstruct device or enhance contrast using imaging software



Technique being employed to study both internal geometries and fluid flow during operation; linked to HPC efforts





K. Neroorkar, R.O. Grover, Jr. et al., "Simulations and Analysis of Fuel Flow in an Injector Including Transient Needle Effects", ILASS-Americas 2012, San Antonio, TX.

Summary of Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
  - Analyzed flow in injector using cyclopentane under two conditions
  - Identified fuel in sac long after pintle closed in both cases
  - Developed technique to quantify fuel mass flow into nozzle
- CT scan of Spray G-type injector
  - Combined neutron CT data with ANL high-definition tip X-ray CT scan ► Result: combined solid model for CFD simulation [ANL*]
- GDI-generated particulate study in GPFs
  - Particulate characteristics continue to demonstrate very different behavior compared to diesel-based particulate
- Regeneration study field-loaded DPFs
  - Significant soot observed in channel
  - Some soot observed in ash plugs

* ACS010 Powell

Technical Accomplishments

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- CT scan of Spray G injector
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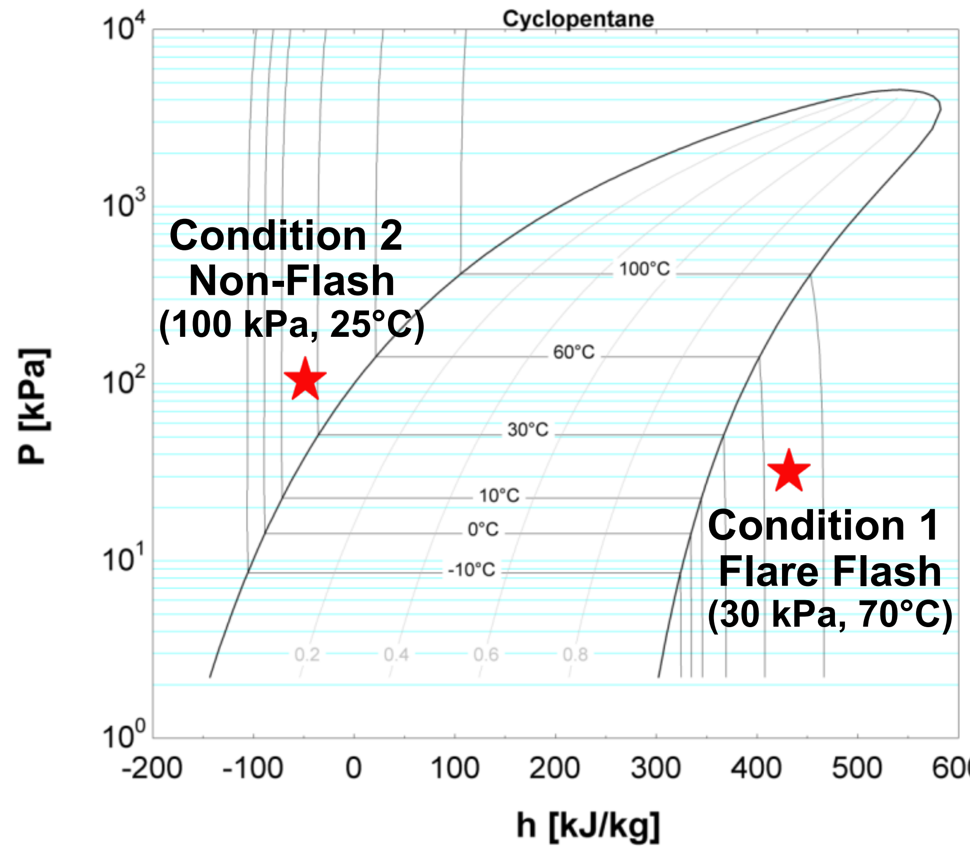
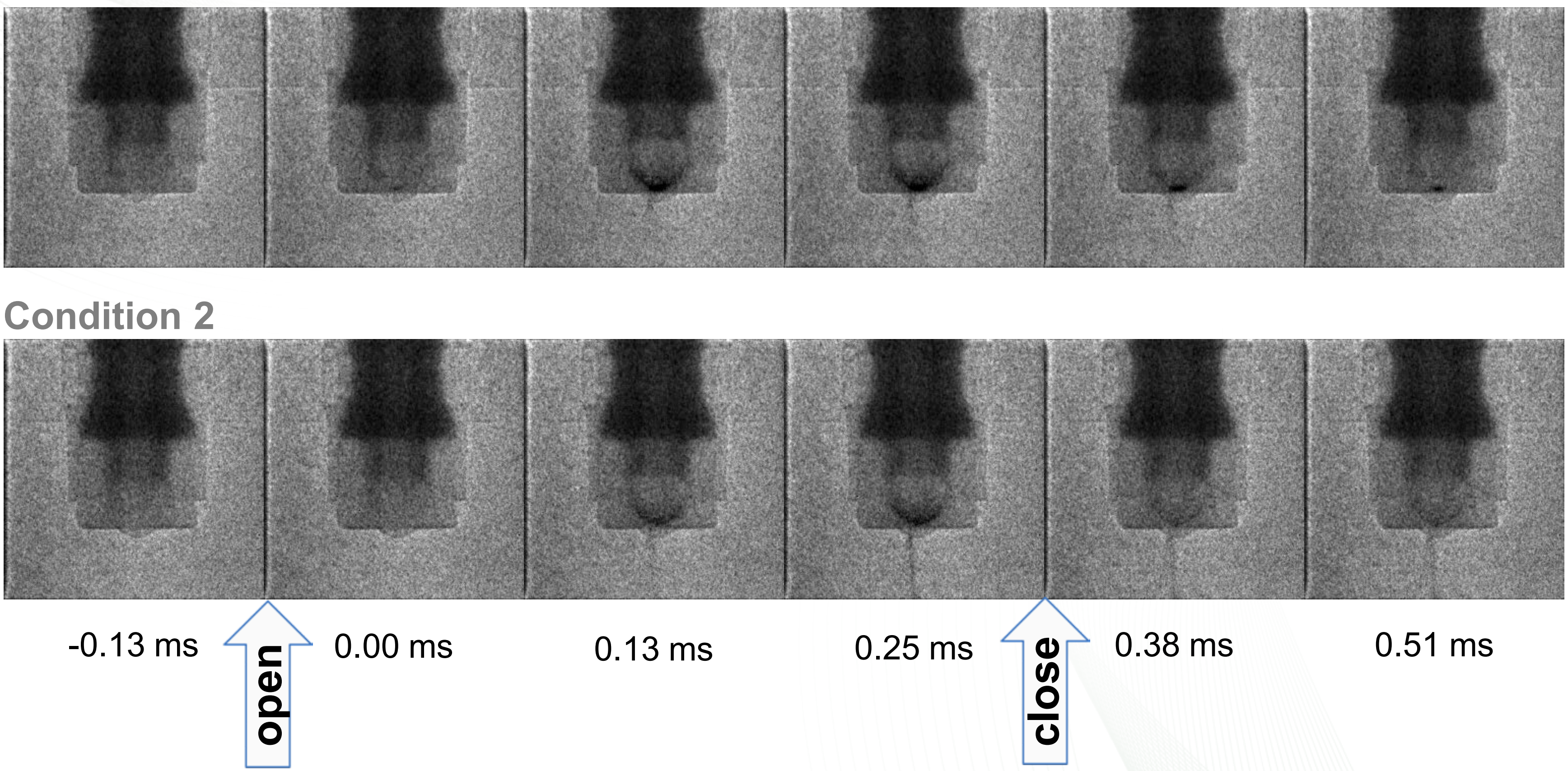
Campaign performed at conditions to minimize fogging and encourage flash evaporation

- Single hole injector from GM
  - Ron Grover and Scott Parrish
- Fuel is cyclopentane
  - Flash boils near ambient
- Injection timing for composite image:
  - 0.367 ms injection
  - 25 Hz
  - 20 μs resolution
    - ~19 frames during injection
    - 1 ms before, 5 ms after injection recorded
  - ~40 s of neutron exposure for each 20 μs frame over 24-40 hours
    - ~2M injections



Fluid behavior at the two conditions differ discernibly

Condition 1

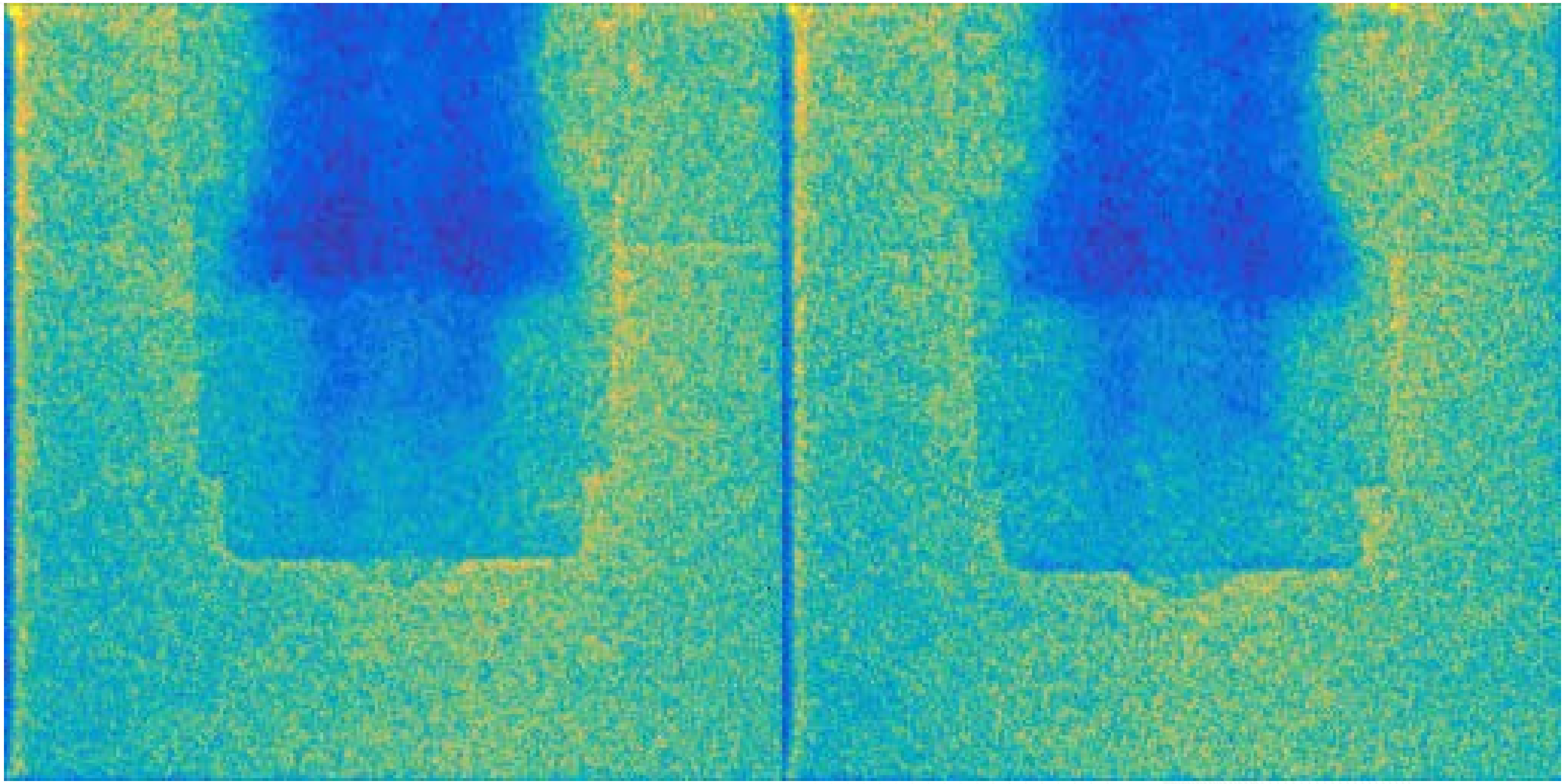


- More neutron attenuation by the fluid is measured in the sac in Condition 1, and more in the spray in Condition 2.

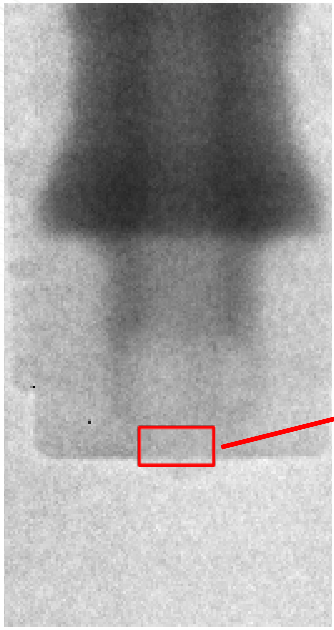
Comparison of injection conditions

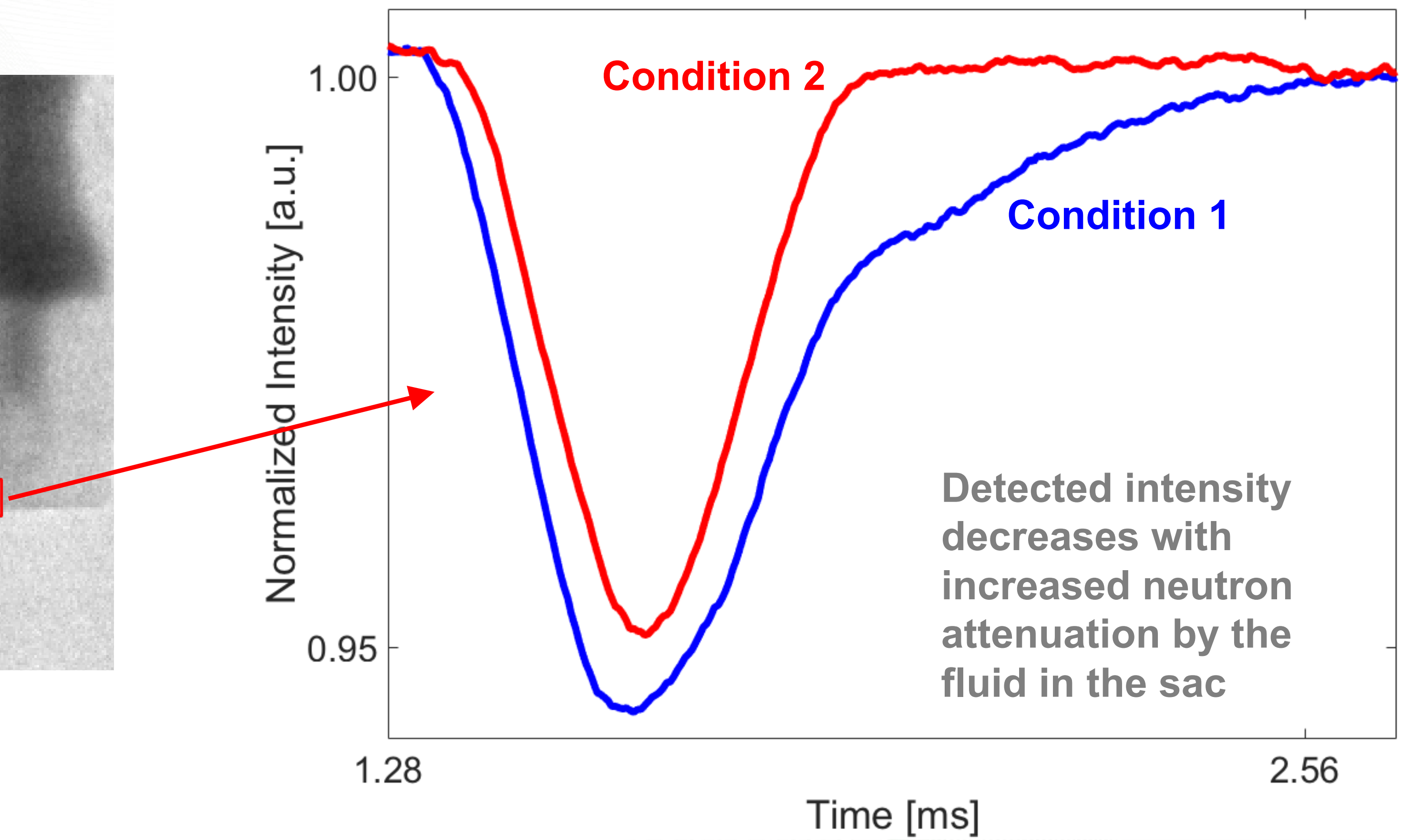
Condition 1 - Flash

Condition 2 – Non-flash



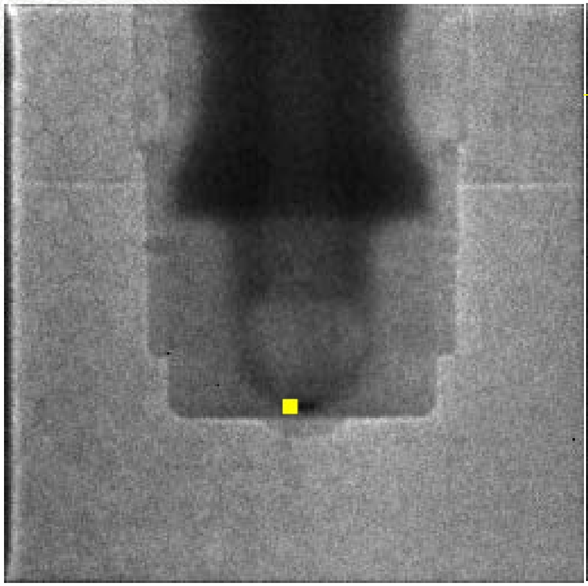
Sac emptying rates differ with condition



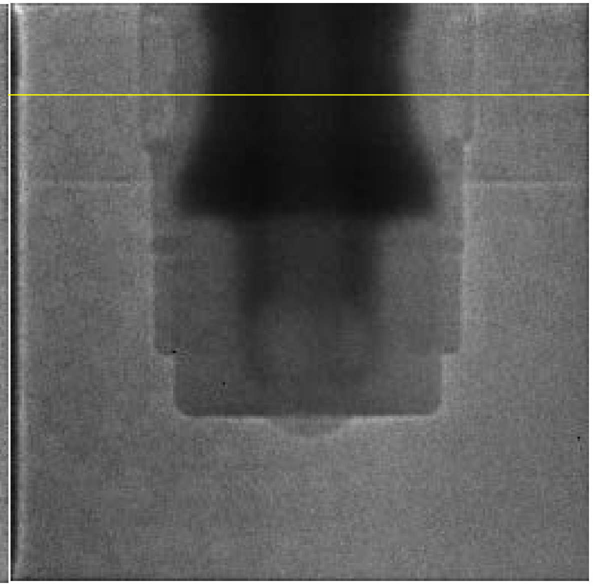


- Condition 1: More neutron attenuation by the fluid is measured, and the sac takes longer to empty.
- Condition 2: Less neutron attenuation by the fluid is measured, and the sac empties very quickly.

With calibrated image analysis, liquid spray mass may be estimated [in progress]

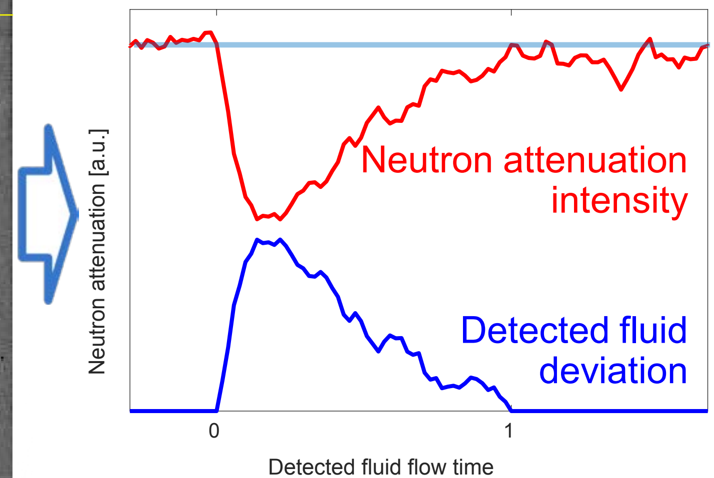


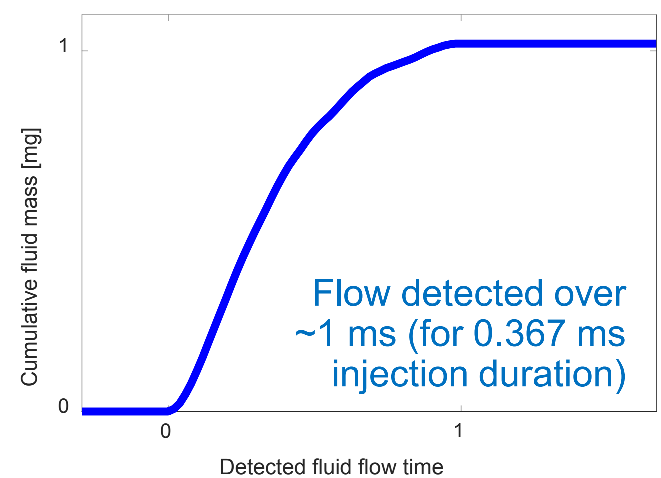
Contrast-enhanced image with sac-nozzle observation area



Raw radiograph with calibration reference line

Attenuation profiles in sac-nozzle observation area





- Based on attenuation, cumulative mass flow past sac-nozzle interface is ~1 mg (target: 1.125 mg). Differences:
  - Vaporization
  - Errors in measurement, calibration etc.
- To do:
  - Validation across all available data
  - Error estimation

Technical Accomplishments

- Dynamic imaging of fluid dynamics inside GDI-based injectors
- CT scan of Spray G injector
- GDI-generated particulate study in GPFs
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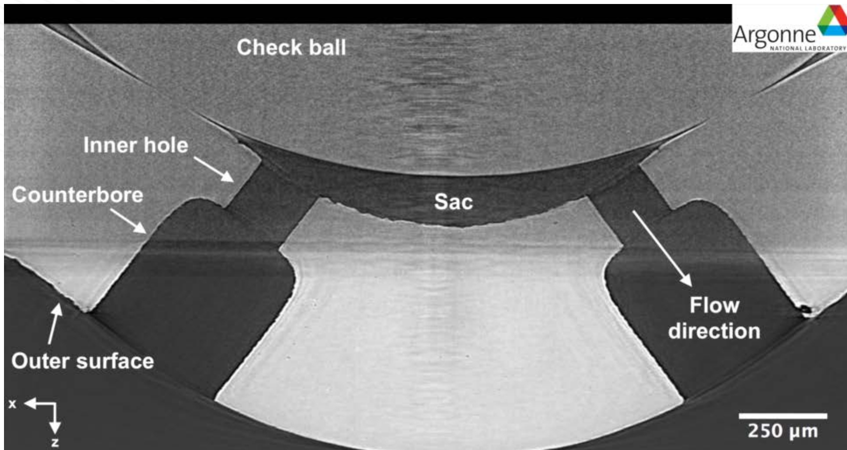
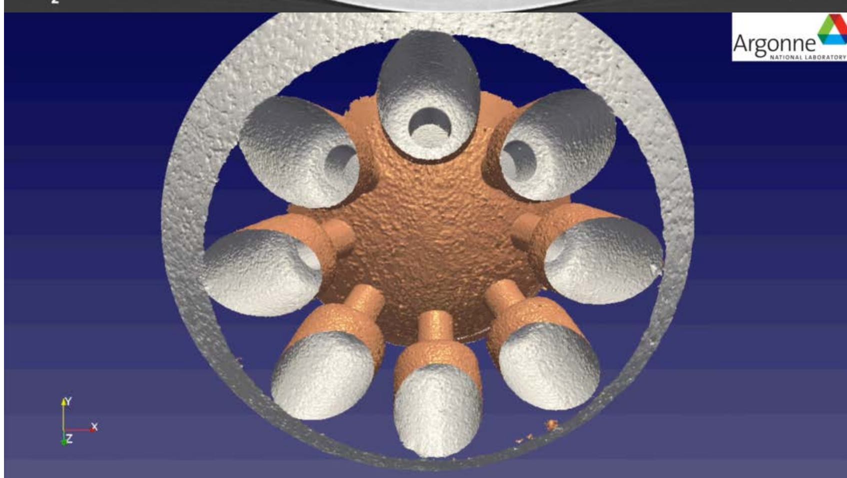
Collaboration with ANL produced full injector scan with maximum resolution

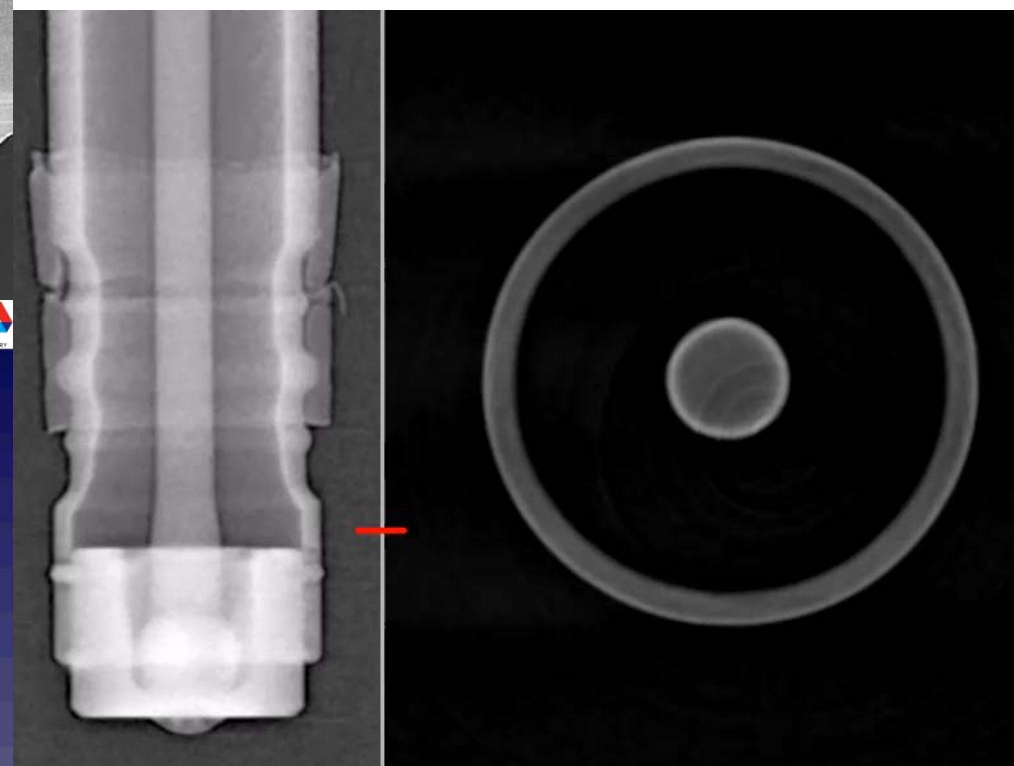
- ANL CT scan of tip shows excellent detail, but imaging sac difficult





https://www.youtube.com/watch?v=XQnNOn91ZP0

- Complementary effort at ANL to complete internal geometry of Spray G-based injector
- X-ray and neutron CT data merged



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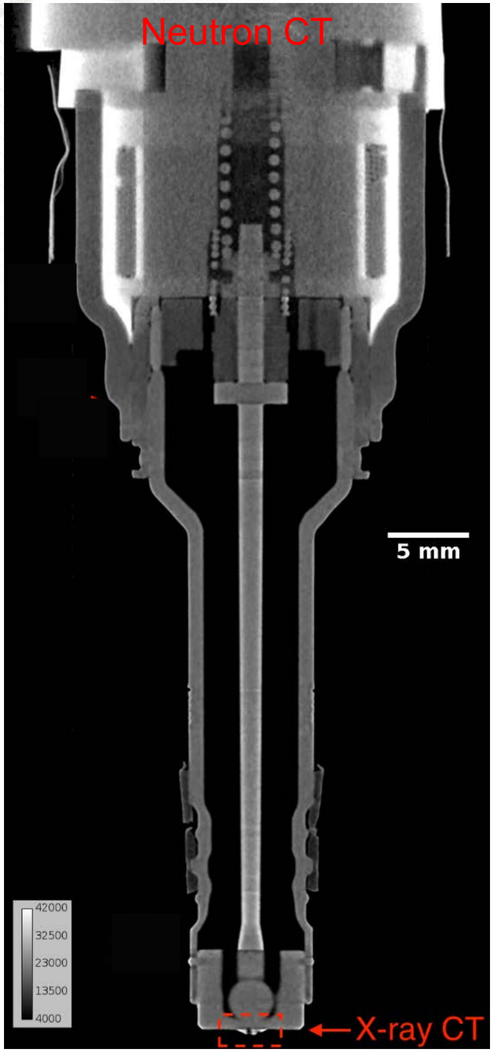

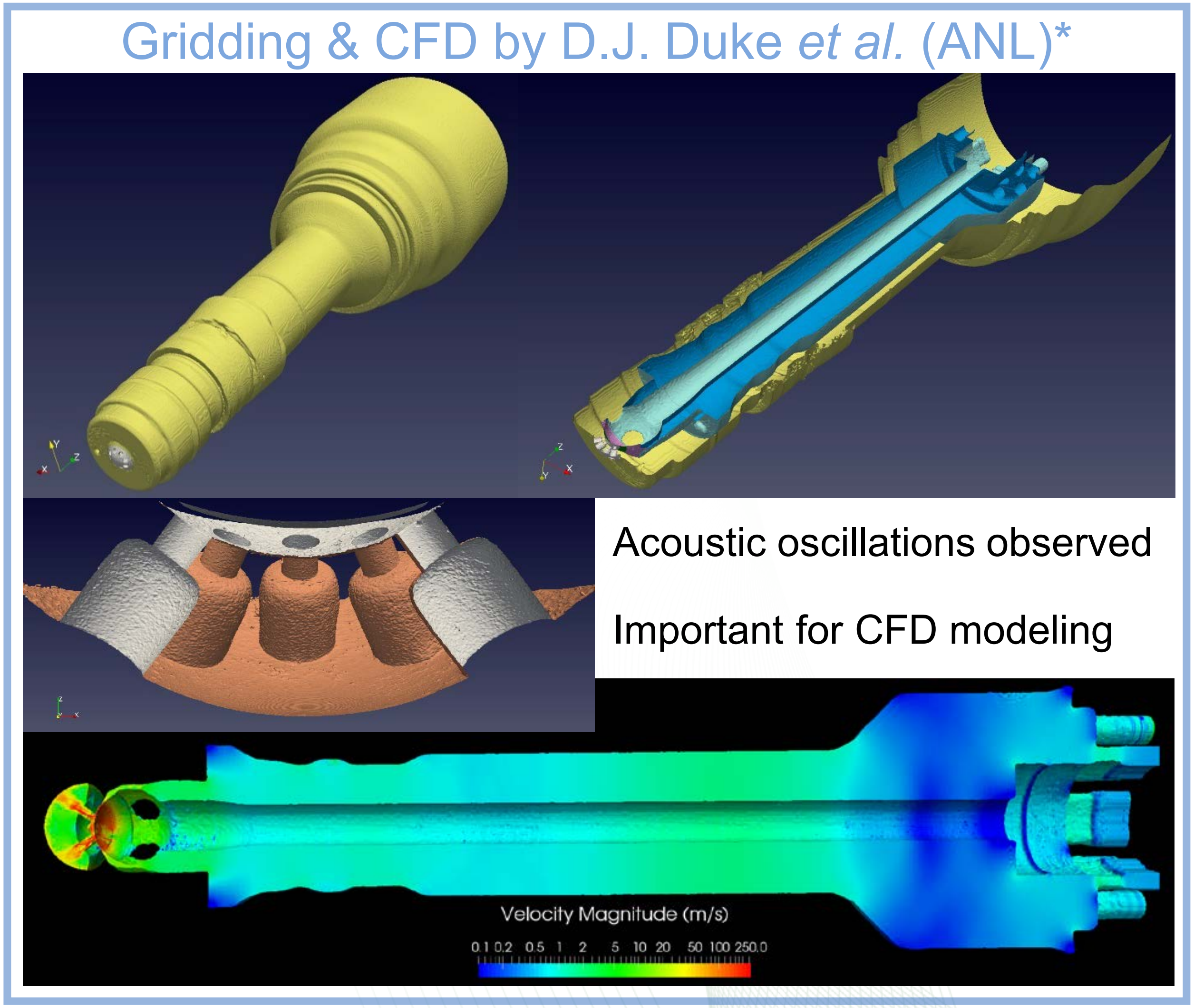

SAE 2017-01-0824

* ACS010 Powell

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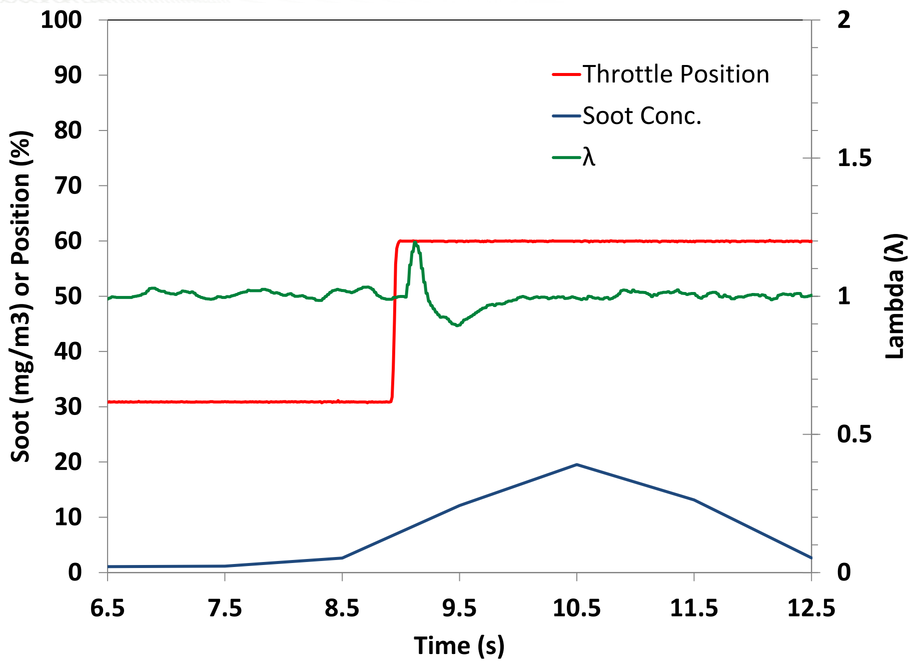
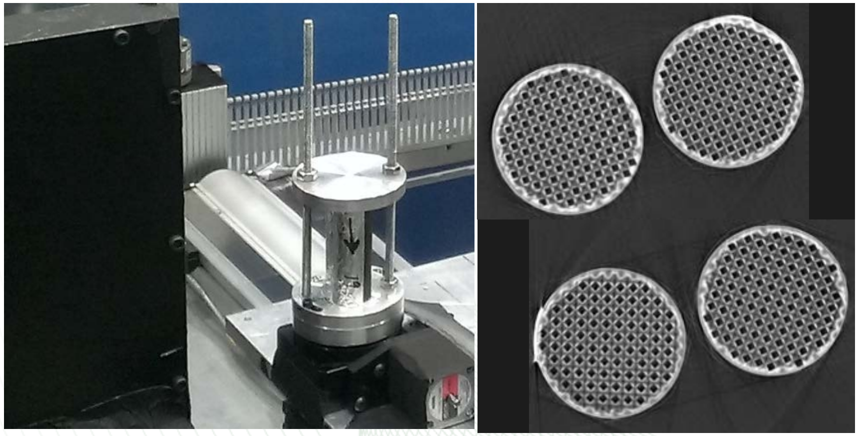
GPF particulate study using tip-in



- GDI stoichiometric engine operated to mimic “tip-in” point of acceleration
  - Novel approach designed to capture mode of maximum PM generation
  - Brief period of rich operation (λ = 0.91), medium-high load
  - Sample holder with four 1” GPFs
    - Allows repeated measurements
    - Filled to nominal 4 g/L
- Characterize with original CCD detector at HFIR



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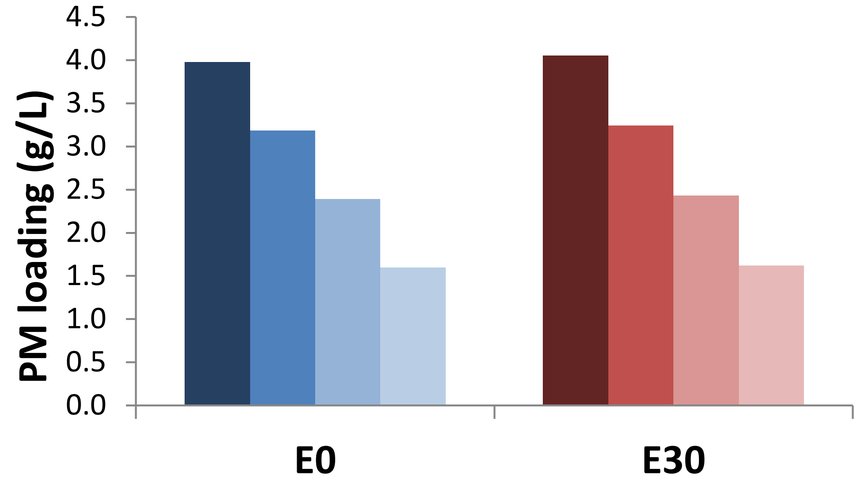
Analysis of GPF particulate deposition and oxidation behavior illustrates its reactivity is different from diesel

- Coordinated with project in Co-Optima program on fuel effects on PM formation/reactivity; E0 vs. E30



[1]Pihl, J.; et.al. (2013) *Top. Catal. 56:499*

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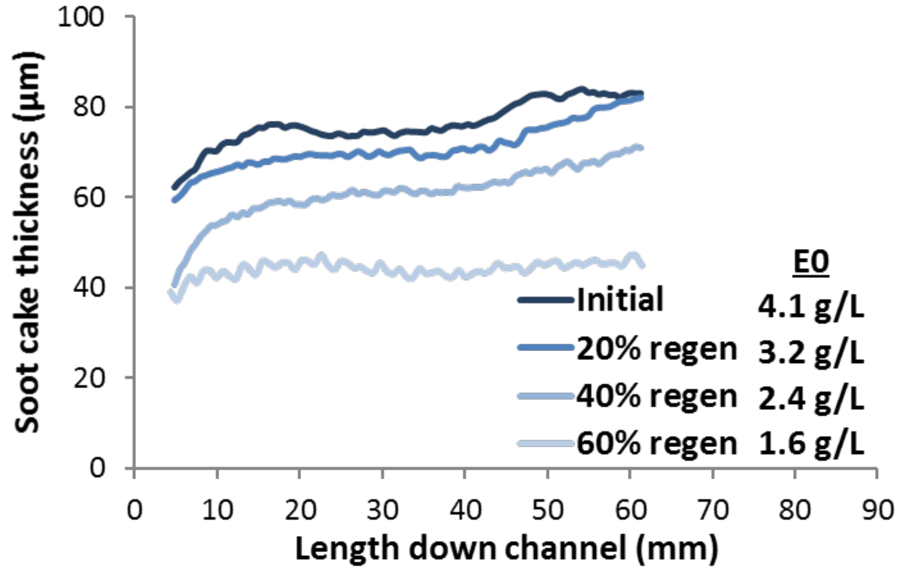
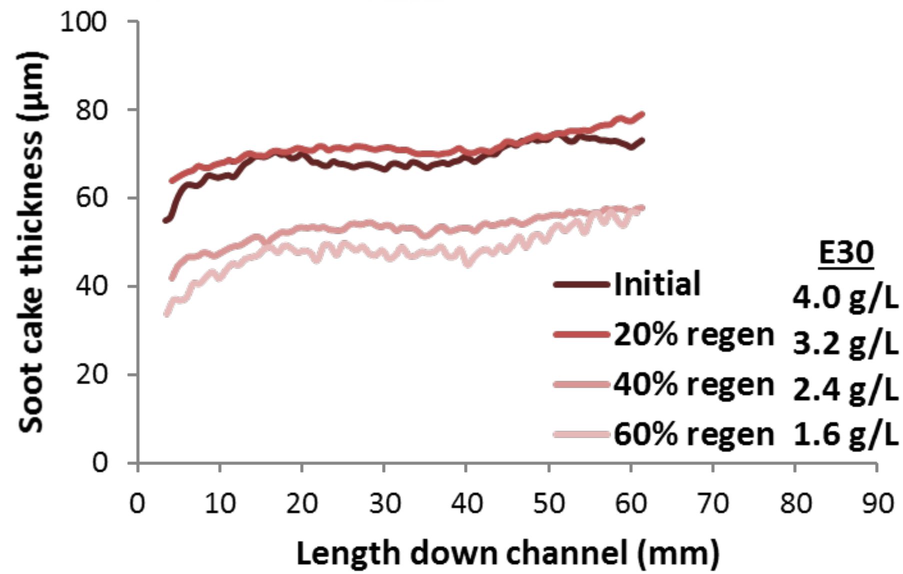
- Minimal decrease in soot cake layer during first 20% regen; after 40% regen, reduction observed
  - Likely adsorbed HC removal
  - Above 40% regen some differences being observed between E0 and E30

Results continue to show GDI-based particulate behaves very different than diesel-based particulate





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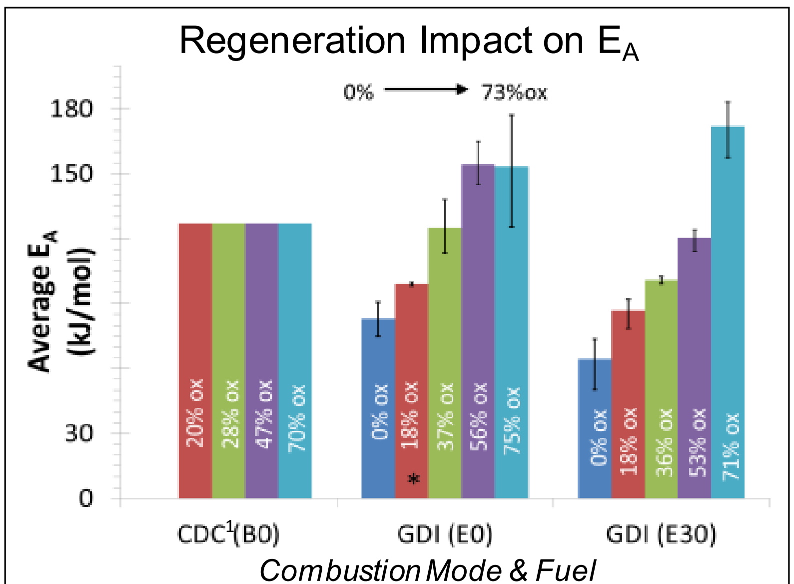
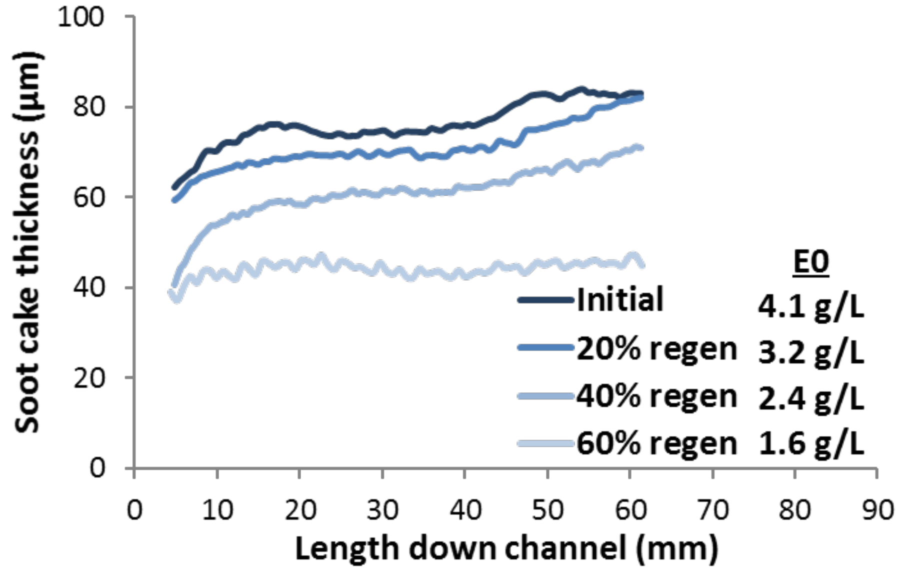
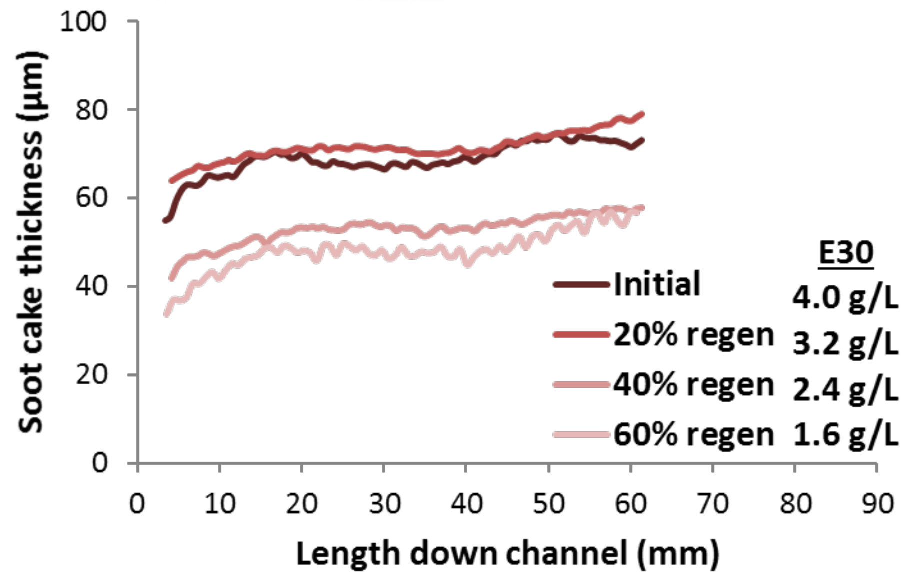
- Oxidation data shows varying Ea in w/ regen







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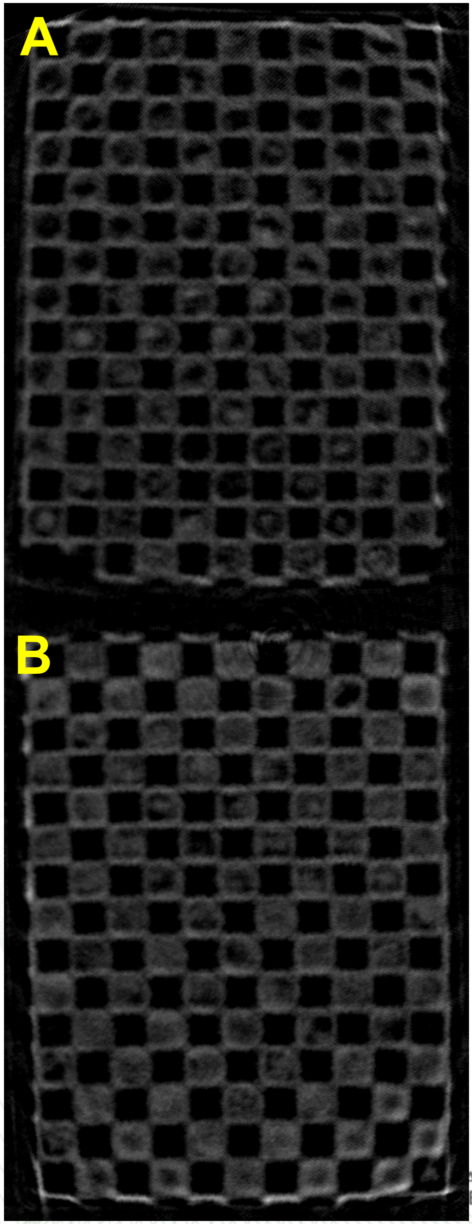
Quantifying soot and ash distributions in DPFs

- Collaboration with MIT
- Complementary work using X-ray and neutron imaging analysis
- Two 12” DPFs with nearly identical field driving patterns
- Physical and X-ray analysis show significantly different ash deposition patterns
- Neutron analysis
  - 1 × 1.5 × 12” rectangular cores
  - Imaged before (ash & soot) and after regeneration (ash only)
  - Examine channels on and upstream of plugs in Sample B, before and after regeneration



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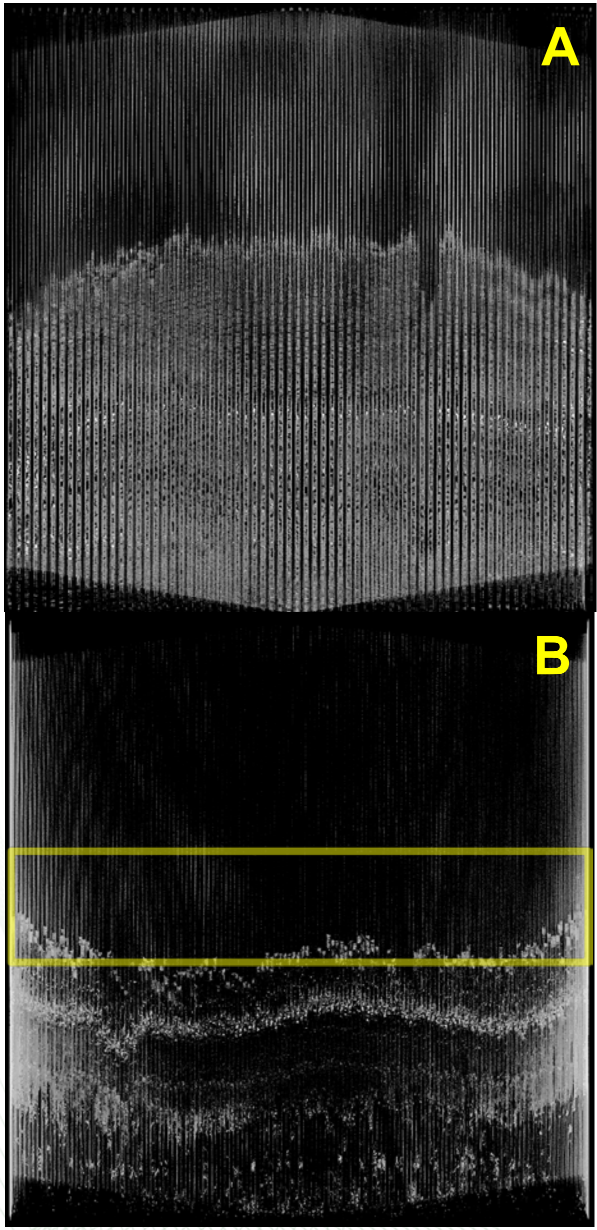
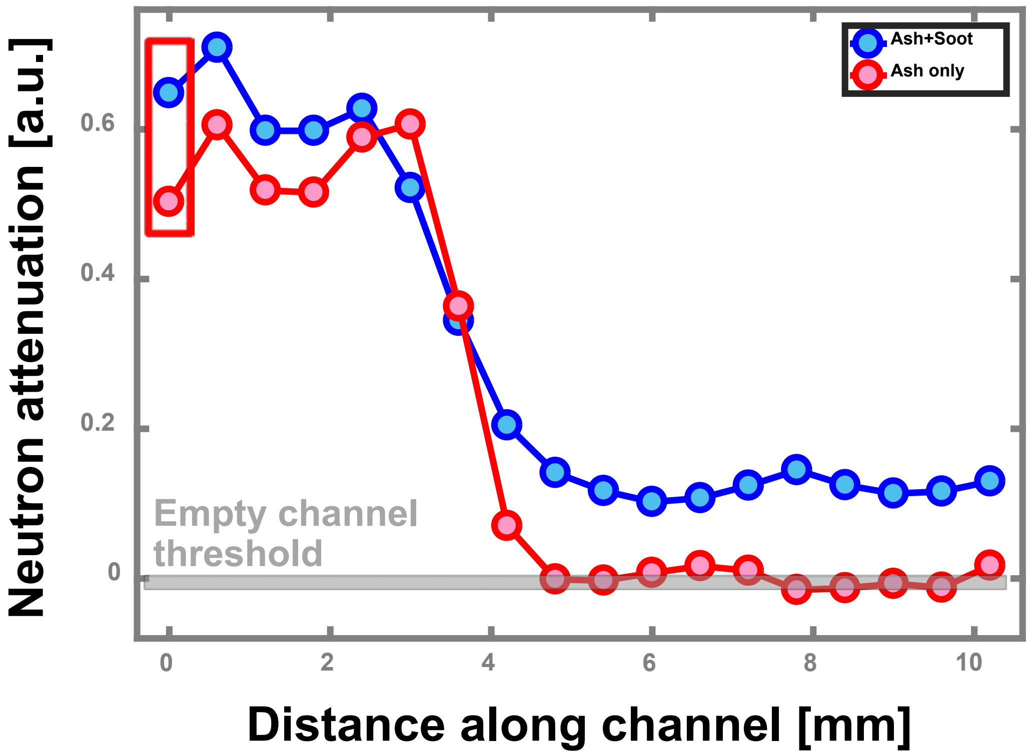
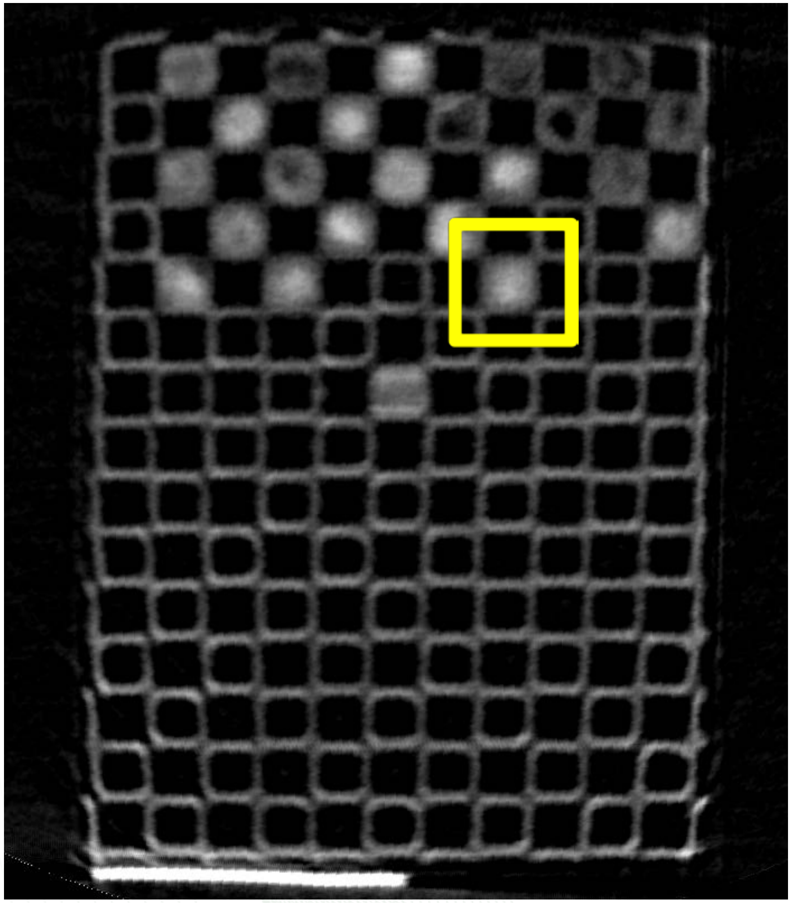


Significant soot was observed upstream of the ash plugs, and potentially some in plugs





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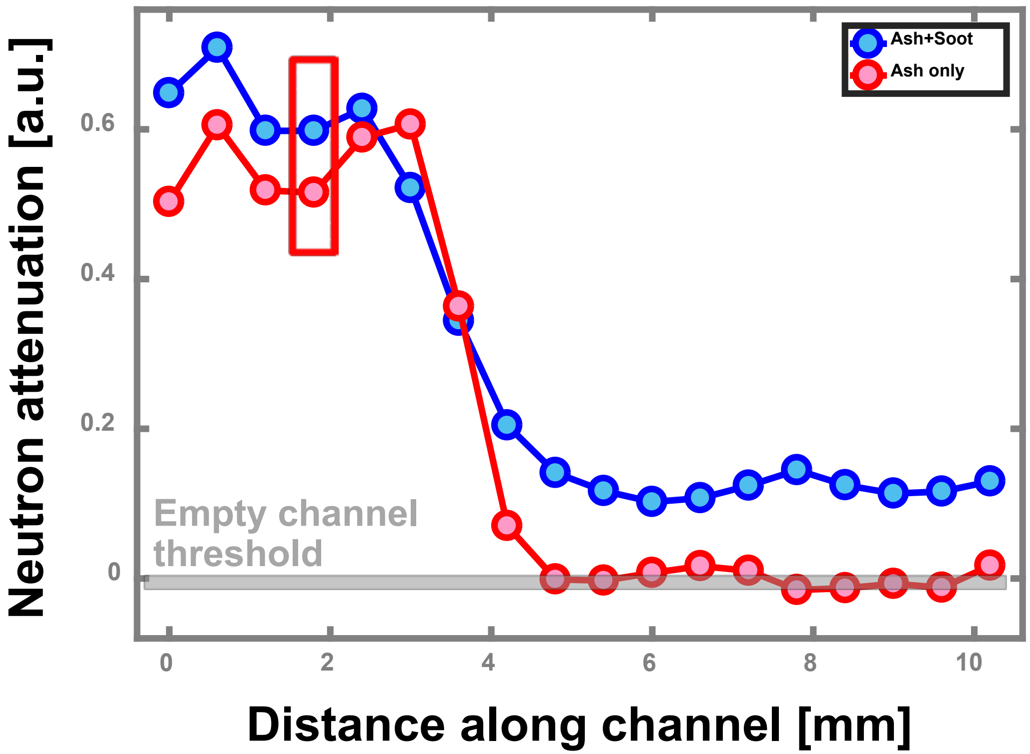

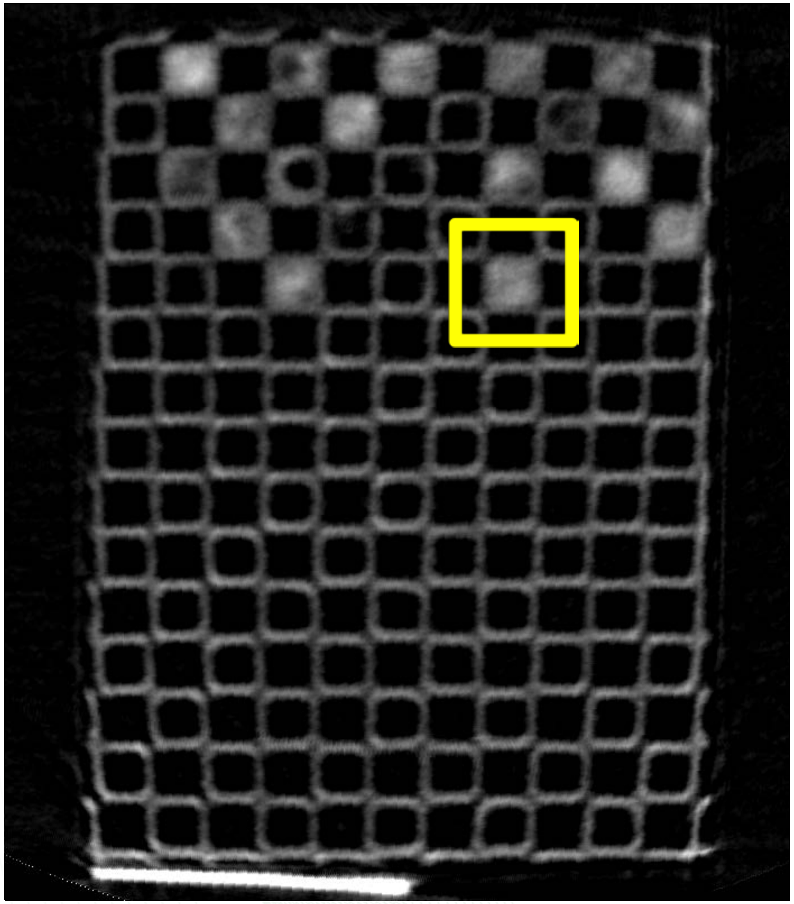

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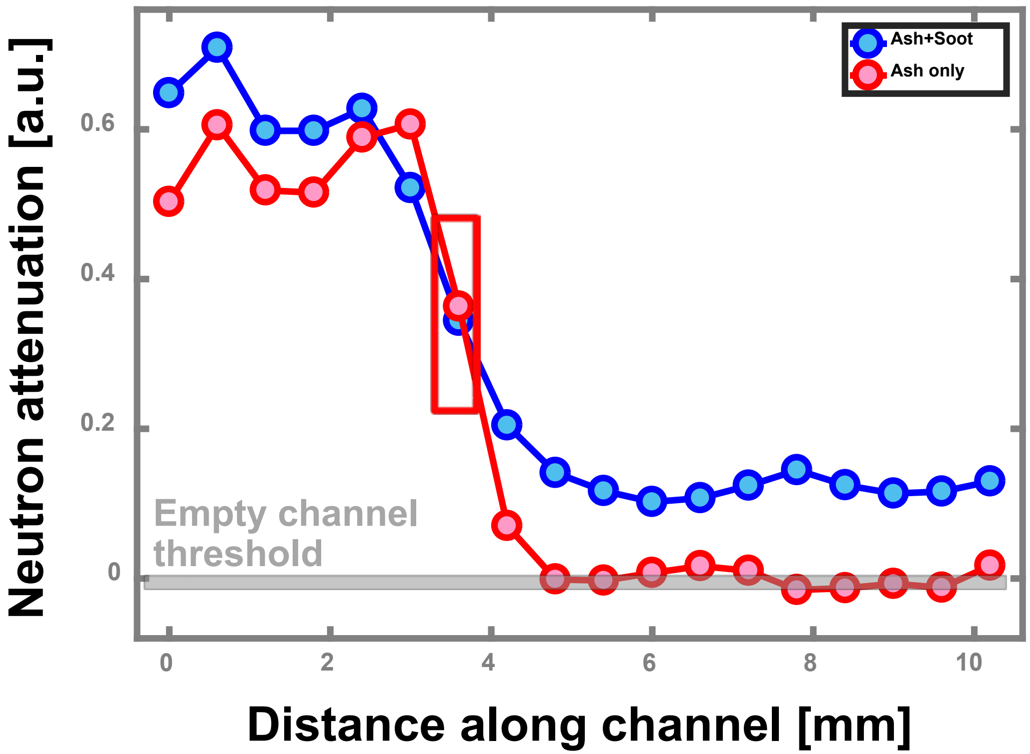

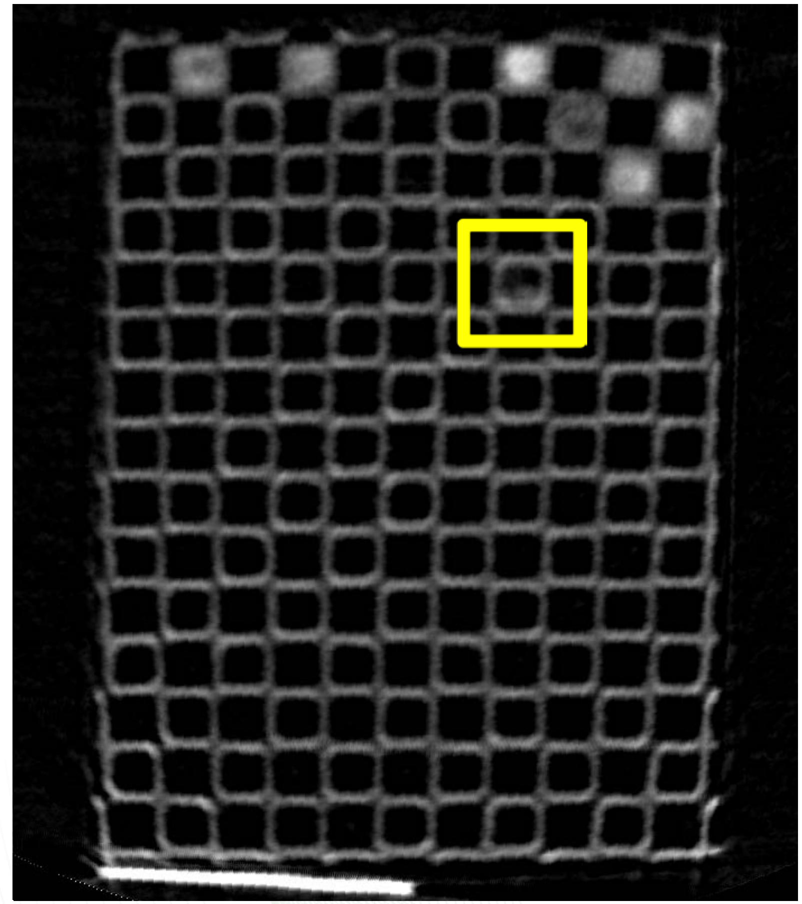

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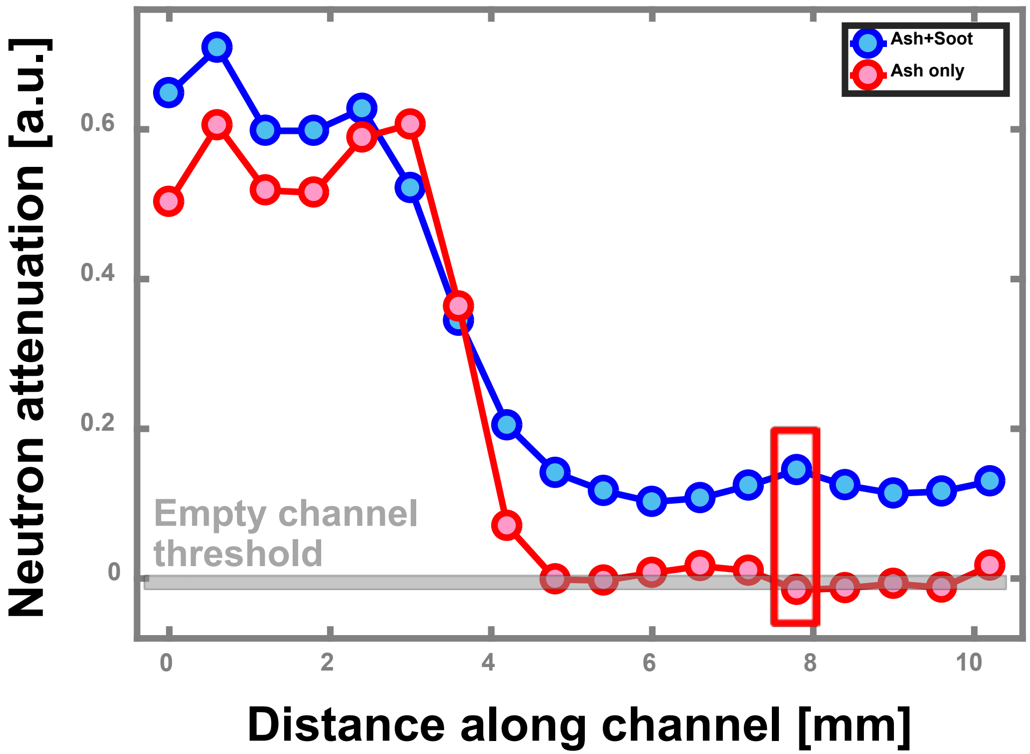
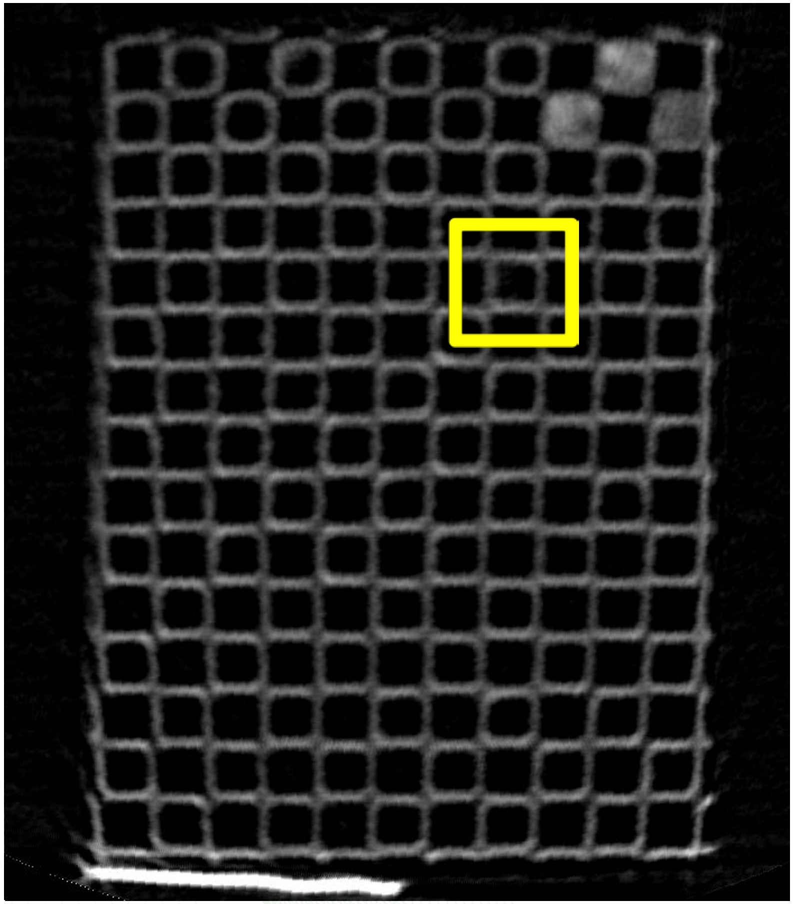


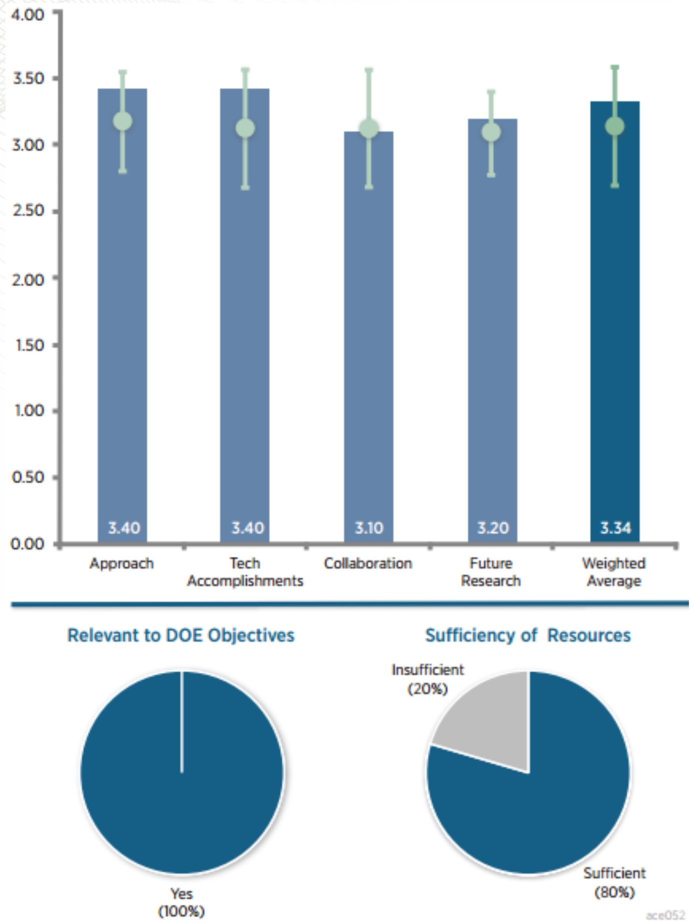


Remaining Challenges & Barriers, and Proposed Future Work

Remaining Challenges:	Future Work:
• Translation of dynamic fuel injection data to modeling	• Improve upon recent progress in image processing and quantitative analysis to benefit modeling • Collaborations initiated with ANL, Boston U., and U. Tennessee
• Unknown effects of double injection events	• Explore inter-injection sac effects during double injections • Flash boiling and non-flash boiling effects on double injections. How much liquid enters the sac, rate of dribble? • Is there a hysteresis in the magnetic field and does it impact pintle movement (explore if study is possible)?
• Unknown behavior of gasoline particulate and how it differs from diesel particulate	• Complete study of full regeneration of GPFs to visualize oxidation characteristics (only one more regeneration level needed, to be completed in particulate-based project)

Any proposed future work is subject to change based on funding levels

Responses to 2016 Reviewers (5)



- **Resources (20% Insufficient)**
  - Comments: more resources needed to accelerate progress
  - Response: progress is moving steadily using allocated resources, but more could accelerate development schedule

- **Approach (3.4/4.0)**
  - Comments: another successful re-tasking for unique DOE resources to aid engine industry… **clear report of complementary work between ORNL and ANL would be nice**… **even better, results**
  - Response: **exchanged neutron data to complement ANL X-ray work on Spray G relevant injector**… **paper presented at SAE in 2017 (SAE 2017-01-0824)**
- **Technical Accomplishments (3.4/4.0)**
  - Comments: **complementary measurements, such as high-speed video, of injector variability could validate the method**… **increased resolution on injector would be nice**
  - Response: **physical access is limited, but laser occlusion of near-nozzle spray might be doable**… **continuing to work with BES researchers to enhance spatial and temporal resolution**
- **Collaborations (3.1/4.0)**
  - Comments: excellent collaboration noted… **engaging injector OEMs could provide direct benefit**
  - Response: **engaging OEMs within confines of limited beamtime**
- **Future plans (3.2/4.0)**
  - Comments: **fouling study would be interesting**… improving geometry description of gasoline injector very useful to community
  - Response: **have collaboration with OEMs interested in fouling, pending beamtime/funding**
- **Relevance (100%)**
  - Comments: reviewers confirmed that the project can help diagnose component behavior related to engine efficiency, and a good use of DOE resources to study problems that industry could not undertake on its own… this project's techniques could become key enablers for high-efficiency engines

Summary

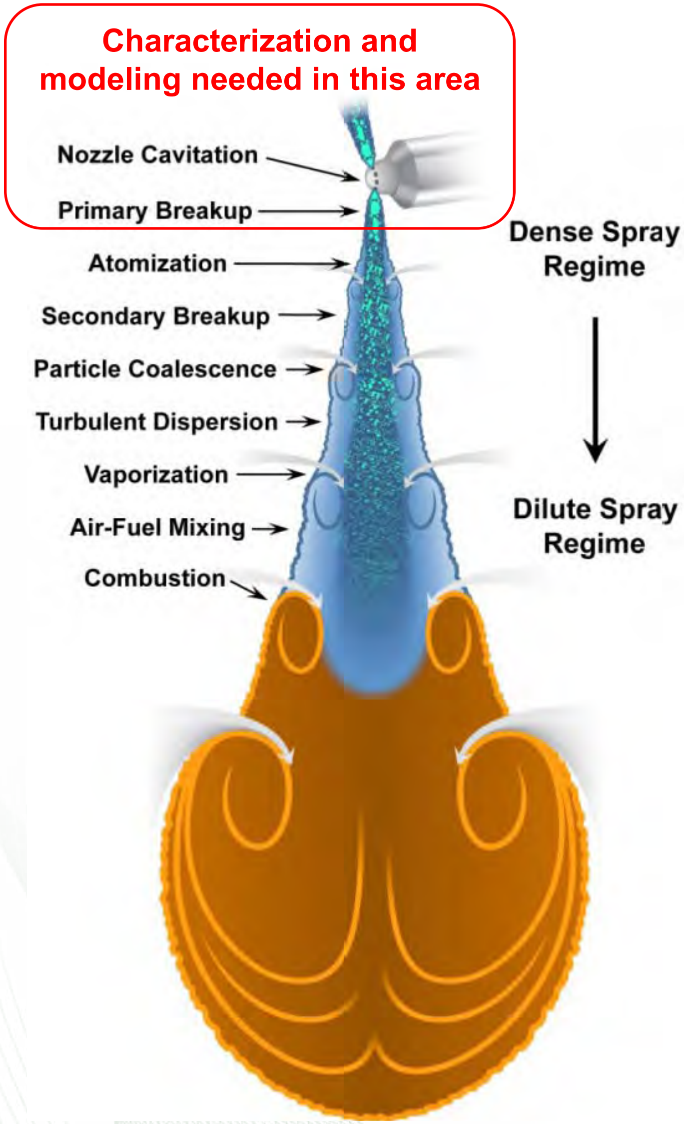
- **Relevance**:
  - Non-destructive, non-invasive analysis to improve understanding of lean-burn vehicle systems, targeting fuel economy improvements and durability; focused on fuel injectors and particulate filters
- **Approach**:
  - Neutron Imaging as a unique tool applied to automotive research areas to visualize, map and quantify deposits in engine parts as well as investigating fluid dynamics inside injector
  - Fuel injectors being studied under both static and dynamic conditions; PFs under static conditions
- **Collaborations**:
  - Partners include BES-funded scientists and programs, Industrial (GM and Continental Automotive), and Academic (MIT, U. Tennessee, U. California and Boston U.), ECN
- **Technical Accomplishments**:
  - Identified and quantified fuel in injector sac long after pintle closed with multiple fuels and conditions
  - Collaborated with Argonne National Laboratory to combine neutron and X-ray CT scans of Spray G-type injector
    - Resulted in complete solid model of production-relevant GDI injector; aids CFD simulations
  - GPF characteristics continue to demonstrate different behavior compared to diesel-based particulate
  - Quantified soot presence in field-loaded DPFs, and illustrated pathway to differentiate soot and ash
- **Future Work**:
  - Explore impact of double injection on sac dynamics, flash boiling, and pintle movement
  - Rectify occlusion from heavy hydrocarbon on walls during dynamic studies
  - Improve image processing and analysis to derive more quantitative data sets for modeling

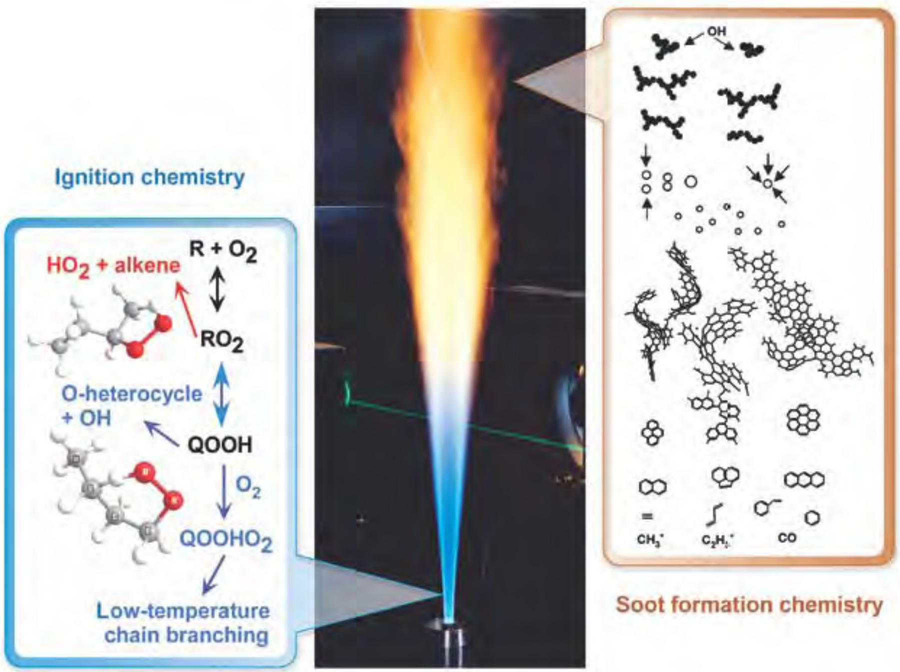
Any proposed future work is subject to change based on funding levels

Technical back-up slides

Spray pattern and impact on product formation has been heavily studied, but critical information is still needed

- Events occurring in the injector impact the spray dynamics and product distribution
  - Products form at different points in fuel spray
- Knowledge of how internal dynamics/events affect the spray pattern are not well understood
- Improved diagnostics critical to make this connection





DOE report, “A Workshop to Identify Research Needs and Impacts in Predictive Simulation for Internal Combustion Engines (PreSICE)”, March 3, 2011.

Employ stroboscopic technique to image internal fluid with ~1 ms injection, 20 μs resolution

- Variables include: rail pressures, heated nozzles and evacuated chamber
  - Highest rail pressures (GDI: ~200 bar)
- Injection timing for composite image:
  - 1 ms injection with 20 μs resolution (50 frames)
  - Targeting 30 s of neutron exposure for each 20 μs frame
  - This is NOT a single shot study
- After proof of principle, move to more realistic systems

One 1 ms injection event

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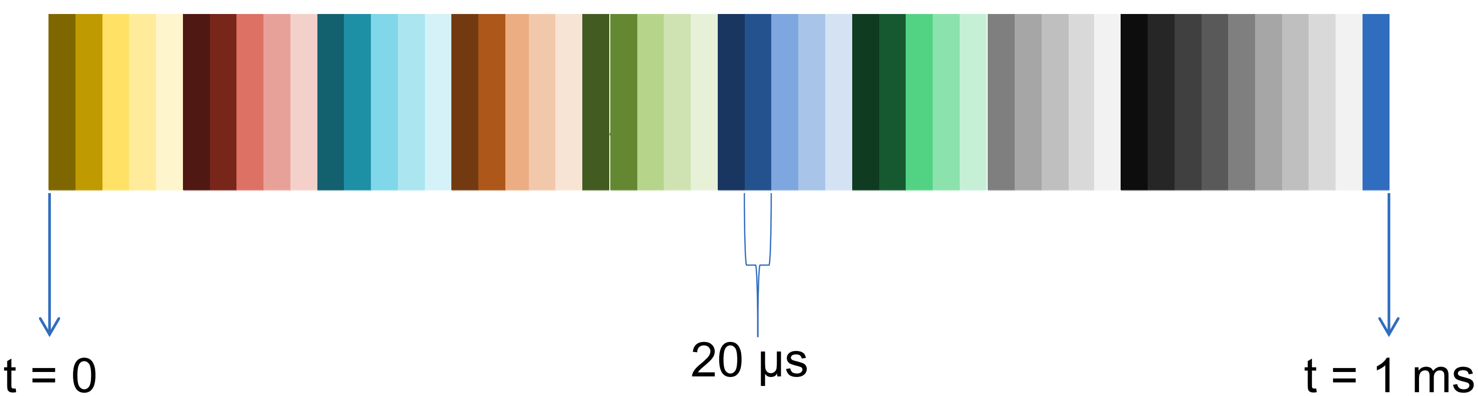

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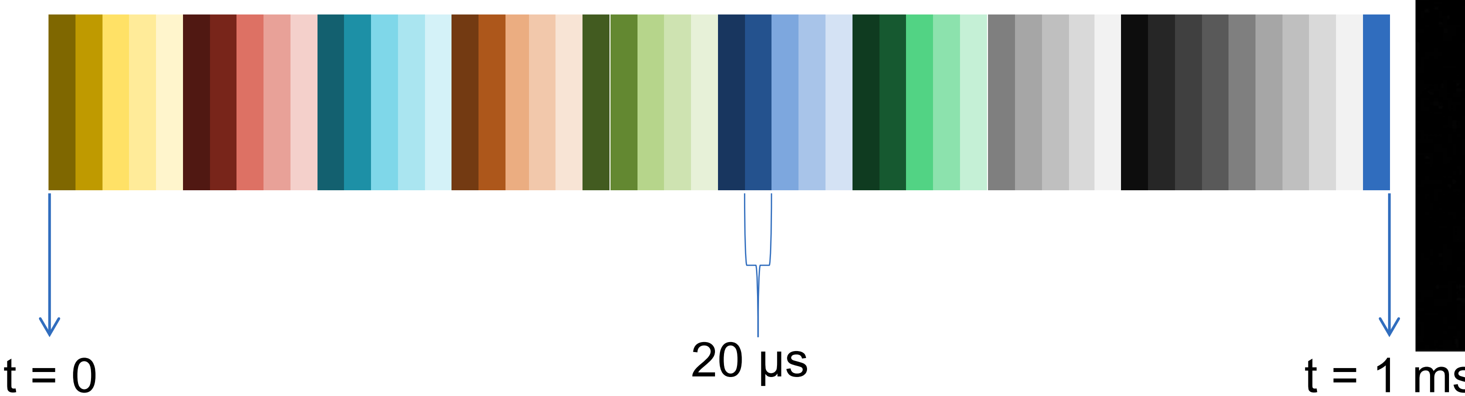
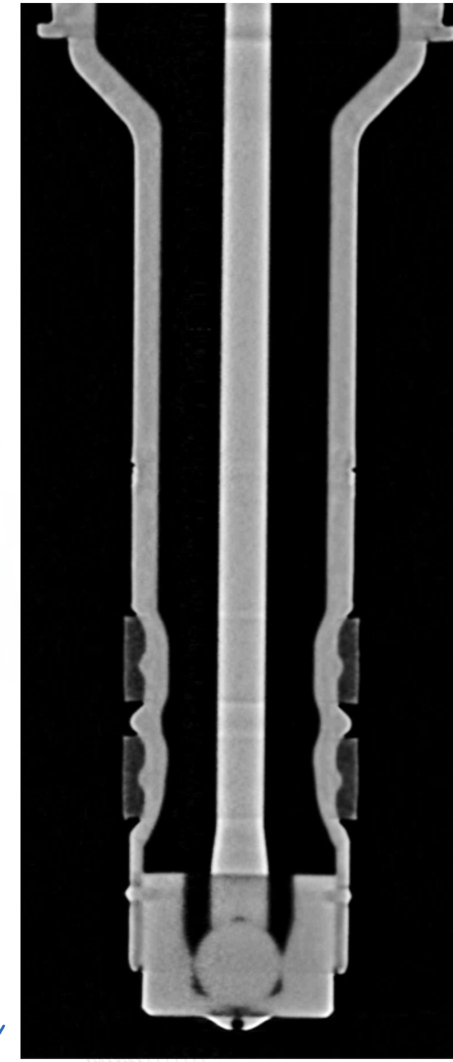
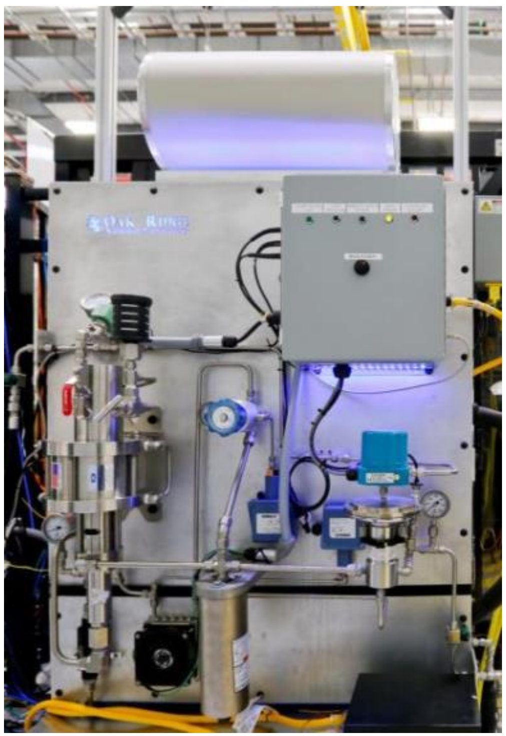


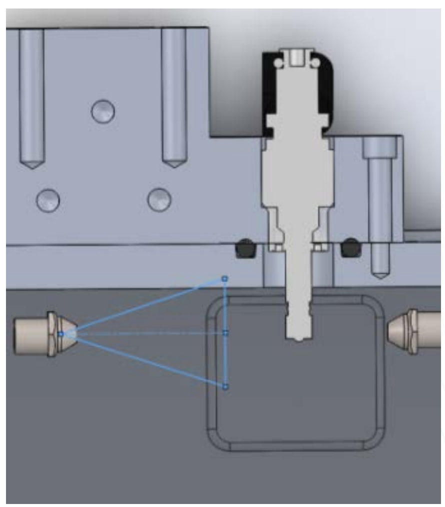


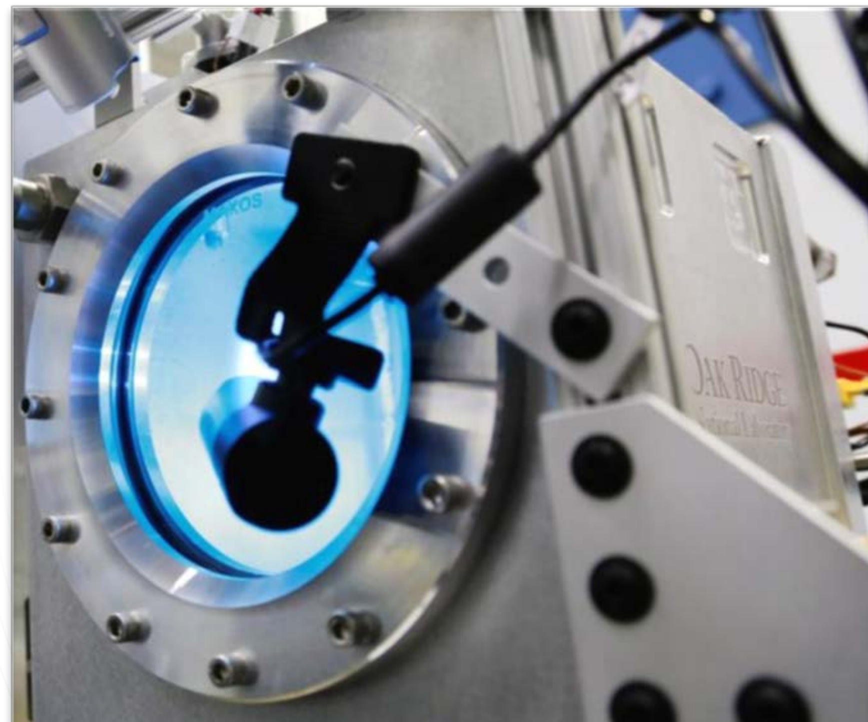
Spray chamber designed to allow for high sweep gas flow, sub-ambient P and elevated temperature

2nd generation chamber

- Multiple cartridge heaters for fuel injector and chamber temperature control (>100°C)
- Modular injector holder built to allow multiple injector designs
- Wide pressure range: 0.01 to 3-4 bar absolute (next generation target 6 bar)
- Direct heated sweep gas with high flowrate pumping system (~8 scfm)







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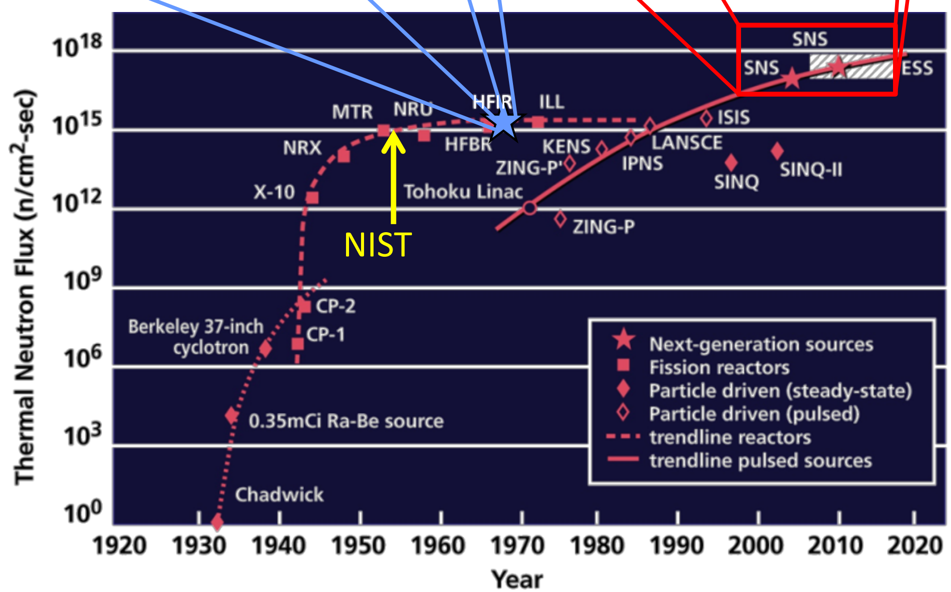
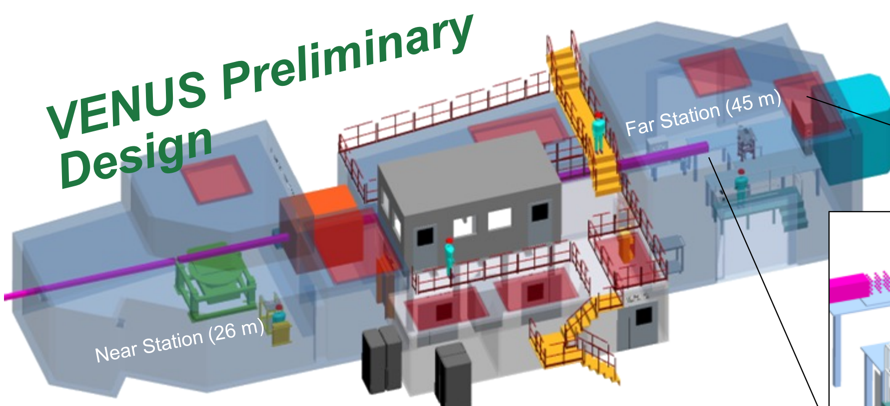
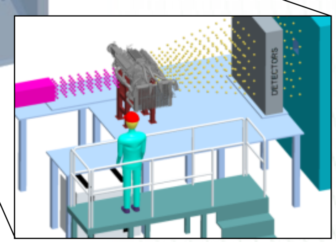
Neutrons at ORNL

- High Flux Isotope Reactor (HFIR)
  - Steady (i.e., non-pulsed) neutron source; “white” beam
  - Imaging beam line accessible through user program
- Spallation Neutron Source (SNS)
  - Most intense pulsed neutron beam in the world; energy selective
  - EERE promised $12M to VENUS imaging beamline; manufacturing
    - 39 months to build



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

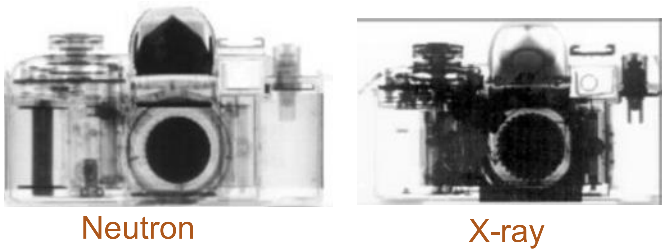


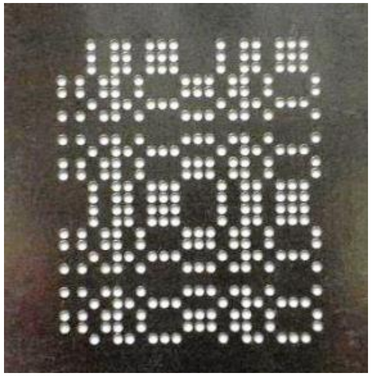


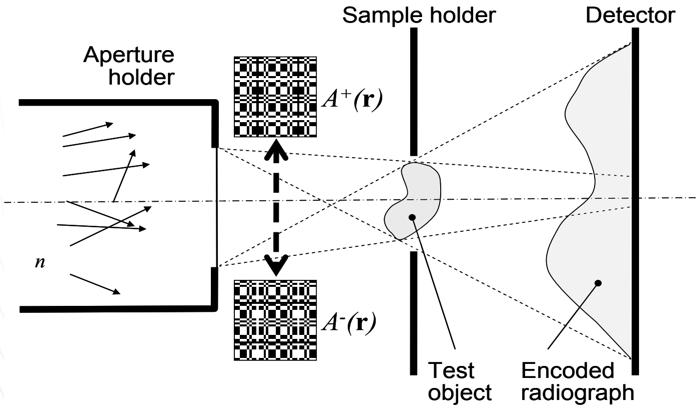
Estimated Beam Characteristics			
Resolution	20 µm	50 µm	200 µm
Max Field of View (cm x cm)	2 x 2	20 x 20	30x30

ORNL is working to extend neutron imaging resolution

- Current resolution
  - Direct imaging (no magnification) limits resolution of neutron imaging to detector system resolution
  - Camera/scintillator system resolution 30-50μm
  - Micro Channel Plate (MCP) resolution 10-20μm
- BES-funded early career award effort focused on improving resolution with magnification
  - Magnification will ease limitations due to detector resolution limit, but source size begins to control resolution
  - Single pinhole for magnified imaging will drastically cut neutron flux
  - Coded source creates many high resolution sources in a coded pattern
  - Resolution Goals
    - 5-10 μm for first coded source imaging system (late 2012)
    - 1 μm for final revision

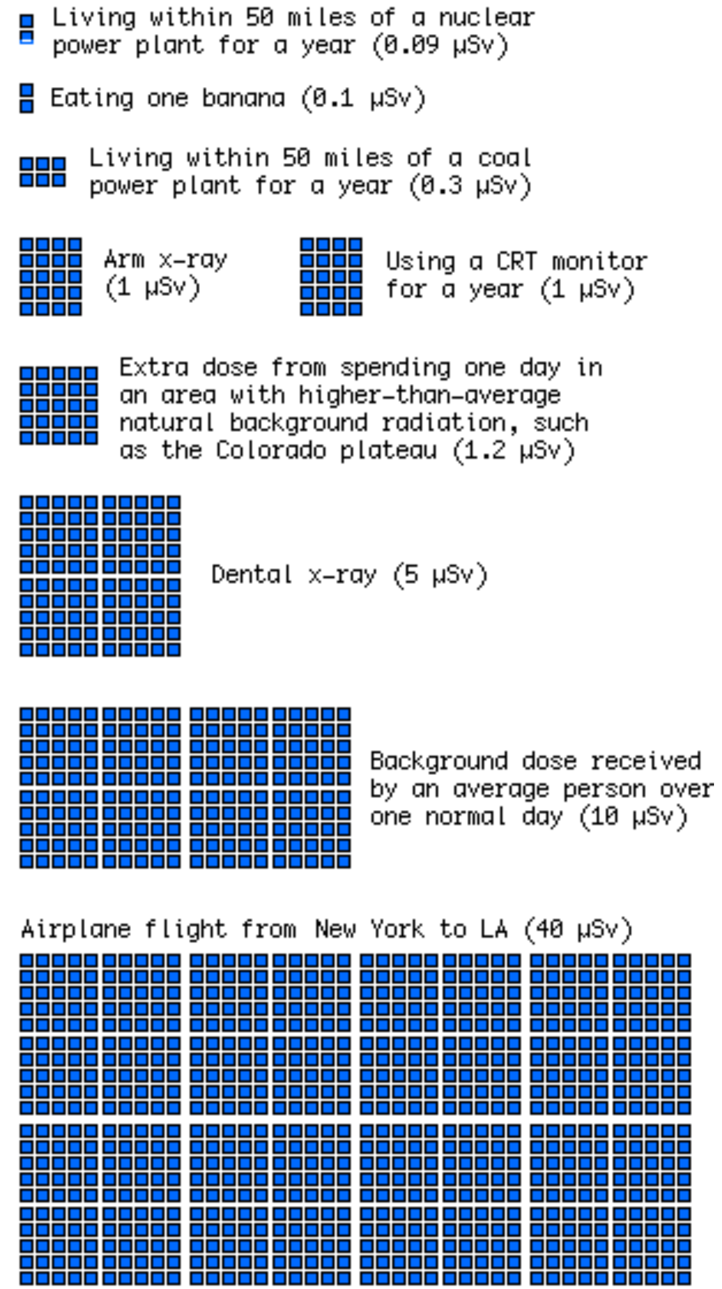






Radiation/Activation

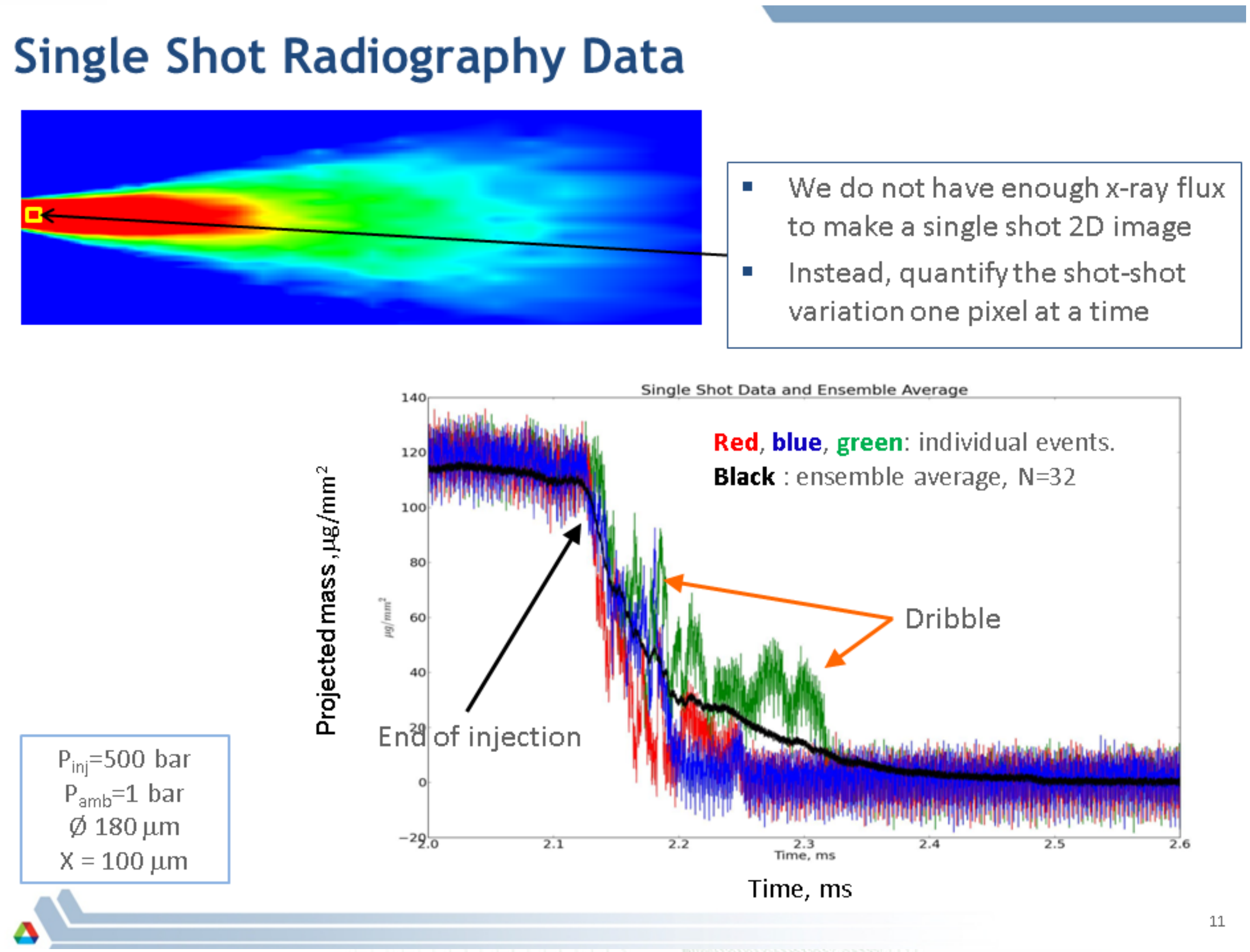
- Average radiation exposure
  - Working at 12 h HFIR, handling specimens: 10-20 μSv
  - Airplane trip Knoxville to DC: ~10 μSv
  - 1 day on earth: ~10 μSv
  - Chest CT-Scan: 7000 μSv
- After exposing materials to neutron beam, they can become “activated”
  - materials give off radiation as they return to their stable state
  - Time of decay varies for materials and time-in-beam
- SiC particulate filters (PFs)
  - After 20 hour CT scan
    - Can be handled within 10 minutes
    - Can be removed from facility within 1 day
- Injectors
  - After 20 hour CT scan
    - Can be handled within 30 minutes
    - Can be removed from facility after ~1 year



“source”: Randall Munroe's Radiation Dose Chart (http://xkcd.com/radiation/)

Argonne National Laboratory (ANL) has shown spray decay/dribble outside of nozzle

- ANL has shown spray dribble occurs after end of injection external of injector
  - Diesel injector shown with different conditions
- Our data corroborates this observation internally and offers complementary analysis



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